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VOLUME XIII NUMBER 5

THE PHYSICAL REVIEW

A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

CONDUCTED BY

EDWARD L. NICHOLS

ERNEST MERRITT, and FREDERICK BEDELL

LXIX

NOVEMBER 1901

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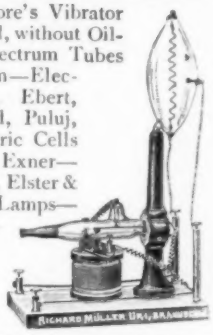

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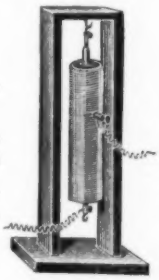

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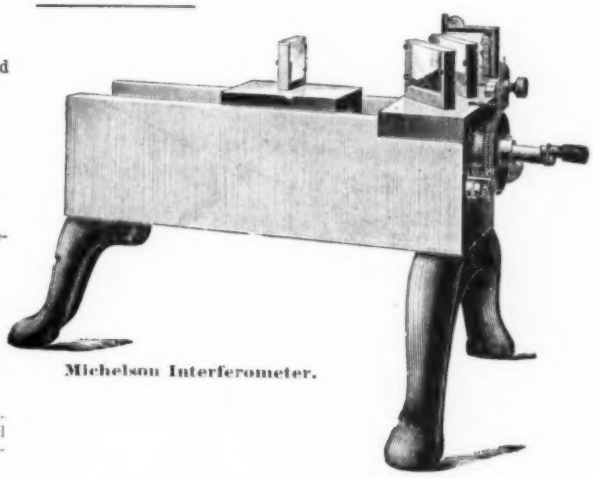

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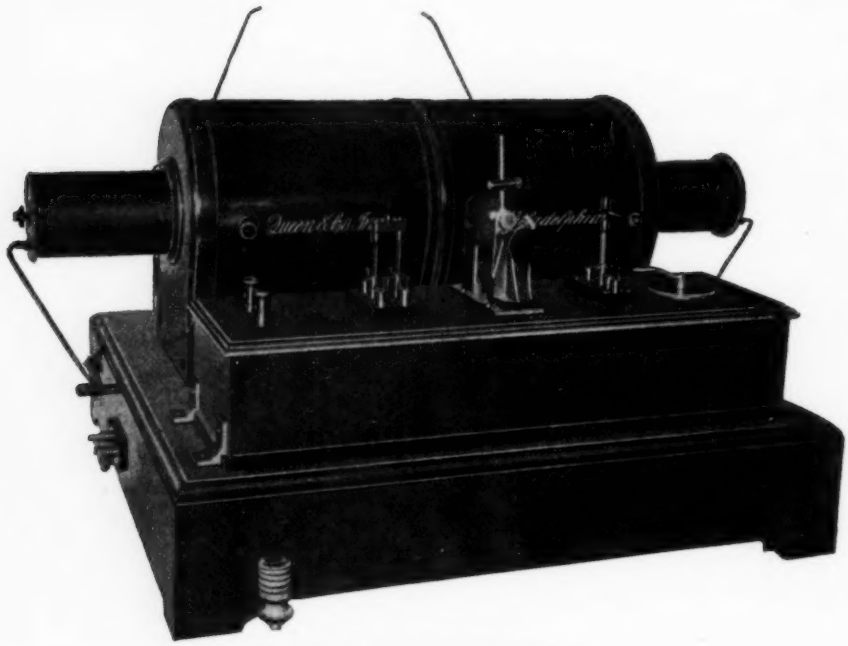

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THE

PHYSICAL REVIEW.

THE DISTRIBUTION OF ENERGY IN THE SPECTRUM OF THE ACETYLENE FLAME.

By George Walter Stewart.

THE published work on the distribution of energy in flame spectra is not very extensive, and some of it is difficult to find, occurring merely as a minor part of a problem considered. As might be expected, the methods and apparatus of the different investigators are quite similar. Lens and mirror spectrometers and also gratings have been used for the production of spectra, and linear thermopiles and bolometers for the measurement of the radiant heat.

Tyndall[1] explored the spectra of illuminating gas and hydrogen flames. He moved a thermopile backward and forward in the spectrum of each flame, and determined the point of maximum intensity, which was found to be farther toward the long wave-lengths with the hydrogen than with the gas flame. Magnus,[2] while working upon the radiation of platinum, found the distribution of energy in the spectrum of a bunsen flame, but his results are not in accord with those of subsequent observers. Langley[3] found the distribution of energy in the flame of illuminating gas, and, from the curve, calculated the radiant efficiency to be 0.024. In a later article[4] he mentions the fact of having also investigated the candle flame, but gives neither curves nor data. Julius[5] obtained the spec-

[1] Tyndall, Annal. der Phys., 124, 1865, p. 36.
[2] Magnus, Annal. der Phys., 124, 1865, p. 476.
[3] Langley, Science, June 1, 1883.
[4] Langley, Phil. Mag., 30, 1890, p. 260.
[5] Julius, Licht- und Wärmestrahlung verbr. Gase; Berlin, Leonh. Simion, 1890.

tral energy curves for flames of hydrogen, carbonic oxide, illuminating gas in bunsen and the ordinary lava tip burners, carbon bisulphide, sulphur, sulphuretted hydrogen, cyanogen, carbonic oxide in oxygen, mixtures of hydrogen and chlorine and hydrogen and bromine, and phosphuretted hydrogen. He also took observations on several parts of the illuminating gas flame. In work upon the emission of gases, Paschen[1] obtained the distribution of energy in the flames of the bunsen and oxyhydrogen flames. He made most accurate determinations of the positions of the bands of CO_2 and H_2O, and these results will be discussed in connection with the work herein described. The results of Rubens and Aschkinass[2] upon the bunsen flame are in agreement with those of Paschen. Lummer and Pringsheim[3] determined the wave-length of the maximum intensity of radiation of several sources of light, and among them the candle and argand burner flames. As it was necessary for them to take observations over merely a small part of the spectra, the only data given are these values of wave-length.

The great value of acetylene, not only for illuminating purposes, but also in experimental research, makes a knowledge of the distribution of energy in its spectrum of considerable importance. In fact, the problem was suggested by a demand which has already arisen in experimental work conducted in this laboratory. In the work here described, a mirror spectrometer and the radiometer of Nichols[4] were used.

I. Apparatus and Adjustment.

1. The Spectrometer.

The spectrometer available was manufactured by Franz, Schmidt & Haensch, Berlin. The mirrors, made by Brashear, had a focal length of 55.7 cm. and an aperature of 9 cm. As it was necessary to keep the radiometer stationary, the mirrow-prism device of Wadsworth was used.[5] Another advantage of this arrangement is that

[1] Paschen, Annal. der Phys., 51, 1894, p. 1.
[2] Rubens and Aschkinass, Annal. der Phys., 64, 1894, p. 584.
[3] Lummer and Pringsheim, Verh. der Deutsch. Phys. Gesell., 1899, p. 215.
[4] Ernest Nichols, Phys. Rev., IV., 1897, p. 297.
[5] Wadsworth, Phil. Mag., 38, p. 337.

any wave-length measured is always at the angle of minimum deviation.

The fluorite prism used throughout the work was a very clear specimen of the purple variety. It was 2.5 × 3 cm. and had an angle of 38° 59′ 55″.

The arrangement of the spectrometer and radiometer is shown in Fig. 1. R is the radiometer; M_1 and M_2 the spectrometer mirrors;

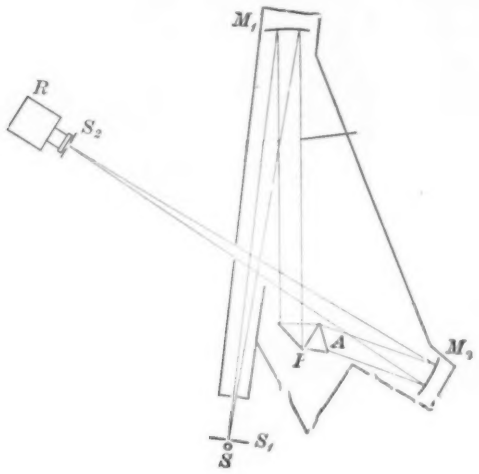


Fig. 1.

P the mirror-prism system; S the source; and S_1 and S_2 two slits of the same width, 0.477 mm. S_2 is placed directly in front of the radiometer and in the focus of M_2, thus avoiding the use of any lens whatever. In order to prevent stray radiation, numerous shields of blackened tin were constructed, but only those about the spectrometer are shown in the figure. As will be shown later, the arrangement was found quite satisfactory. The shutter operated to give deflections and zero readings was placed at A. The radiometer could not be conveniently mounted on the arm of the spectrometer, and although they stood on the same support, there were changes in their relative positions which caused considerable annoyance.

The refractive indices used in the computations are due to Paschen.[1]

[1] Paschen, Annal. der Phys., 56, 1895, p. 765.

Adjustment on the Sodium Line.—It was necessary to have an accurate method of causing the sodium line, or any other known part of the spectrum, to fall upon the slit S_2. This method had to be not only accurate, but also simple, for, owing to slight changes in the relative positions of the radiometer and spectrometer, it was necessary that the adjustment be repeated quite frequently.

The radiometer was adjusted so that its fluorite window was not quite perpendicular to the incident beam, the reflected light returning in the neighborhood of M_2. The apparatus C in Fig. 2, consisting of a long focus lens and two mirrors, could be lowered into the spectrometer in the region of the reflected beam. The light from the fluorite window would then pass through the lens and be reflected from the mirrors into the microscopic eyepiece D, Fig. 2. Whenever an adjustment on the sodium line was desired, sodium light was produced in front of the spectrometer slit, the prism table was turned until in the proper position for this wave-length, and C was lowered into the spectrometer. The position of the spectrometer was now shifted until the eye at D saw that the image of S_1 coincided with S_2. The radiometer slit was then upon the sodium-line. The error introduced by this method was about 3 seconds of arc as read on the spectrometer, or less than 0.002μ at this point in the spectrum.

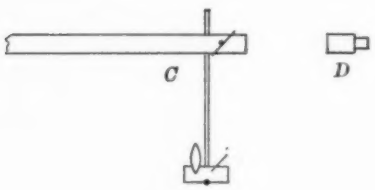


Fig. 2.

2. *The Radiometer.*

(*a*) *Construction.*—There was at my disposal a radiometer which had been constructed according to the description of Nichols.[1]

This instrument, modified to suit the work undertaken, is shown in Fig. 3. The bronze block was 5 × 5 × 10 cm., and the vertical boring 3 cm. in diameter. There were two lateral borings; the one in front of the vanes was 2 cm. in diameter, and the one in front of the mirror, not shown in the figure, was elliptical and longer on the outside. From the crossbar resting on a shelf on the interior just

[1] Ernest Nichols, Phys. Rev., IV., 1897, p. 297.

below the top, was hung the vane and mirror suspension. The crossbar fitted loosely in the boring so that the suspension could be shifted horizontally. In front of the vanes was a thin sheet of mica supported by a brass cylinder which fitted in the lateral boring. The window which had been at *a* was discarded, and in place was soldered a brass tube closed at one end, but with an aperture as shown in the figure. A mixture of beeswax and tallow was rubbed upon the ground surface of this partially closed end. A fluorite plate, 4.5 mm. in thickness, was then pressed firmly into place. A piece of mirror glass was sealed over the other window in a similar manner. If the metal surfaces were first slightly warmed, then, when the fluorite and glass were put into place, there resulted joints which were, so far as the writer could observe, perfectly air-tight. For a top, the neck of a round bottle was utilized. Into this neck was ground a glass tube which led off to a stopcock, and thence through two rubber-mercury seals to the mercury pump. The same mixture of beeswax and tallow was used at all four joints at the radiometer. Melted beeswax was poured into the bottle-neck to prevent that joint being disturbed when the top was removed.

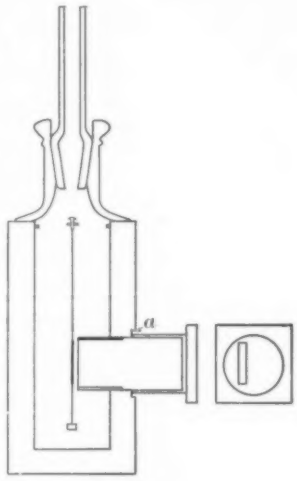


Fig. 3.

The deflections of the mirror were read by the telescope and scale method.

Two different suspensions were used. In both the vanes were approximately 2 × 15 mm., and were fastened together by glass fibers, the distance between them being about 1.5 mm. The mirrors were about 2 × 3 mm. The vanes, mirror and fibers were fastened by shellac.

In the first suspension, which was used in exploring the visible spectrum, the vanes were of thin mica coated with lampblack. A firm black coating was obtained by first dipping the mica into a very dilute alcoholic solution of shellac, and then holding it above a piece

of burning camphor. The loose particles were then wiped off gently, and the operation repeated until a coating sufficiently thick was obtained. The weight of this suspension was 4.2 mg. The quartz fiber, by which it was suspended, was so fine that even at the point of maximum sensitiveness the system was aperiodic, and one had to wait five minutes in order to take one reading.

In the second suspension platinum-black was used. While lamp-black and platinum-black are far from being perfect absorbers of long rays, yet the absorption of the latter covers a much wider range than that of the former.[1] According to Kurlbaum,[2] platinum-black is preferable for all experiments, not only because of its better absorption, but also because of its greater conductivity, and above all because a uniform layer is deposited and the degree of absorption can be defined by the data of electrolysis. By determining the ratio of emission of different thicknesses of these two absorbers to that of an ideally black body and assuming Kirchoff's Law, he has found the percentage of radiation which will be absorbed by layers of different thickness. He shows that a layer of platinum-black $190\frac{mg}{dm^2}$ absorbs almost 97 per cent. and fully as much as a layer of twice that thickness.

The composition of the electrolyte as given by Kurlbaum and as used in this case, is 1 part platinum chloride, 30 parts water, and 0.008 part lead acetate. An attempt was made to deposit the platinum-black upon aluminium foil; but it failed because the aluminium was attacked by the solution. This would not have been wholly unexpected had the writer been aware that what is commonly called platinum chloride is really chlorplatinic acid. Platinum foil then seemed to be the most practicable material for the vanes. Pieces were rolled to the thickness of about 0.01 mm., a thin coating of shellac placed on one side to prevent electrolysis, and the platinum-black deposited. The layer obtained was about $250\frac{mg}{dm^2}$. The weight of this suspension was about 15 mg. The fiber was not so fine as in suspension number one, and at the point of maximum sensitiveness the time required for a deflection was about 40 seconds.

[1] Rubens and Nichols, PHYS. REV., IV., 1894, p. 314.

[2] Kurlbaum, Annal. der Phys., 67, 1899, p. 846.

(*b*) *Sensitiveness.*—As is well known, the sensitiveness of the radiometer does not continue to increase with higher vacua, but reaches a maximum. The following curve was taken to show this point, the pressures being read with a McLeod gauge.

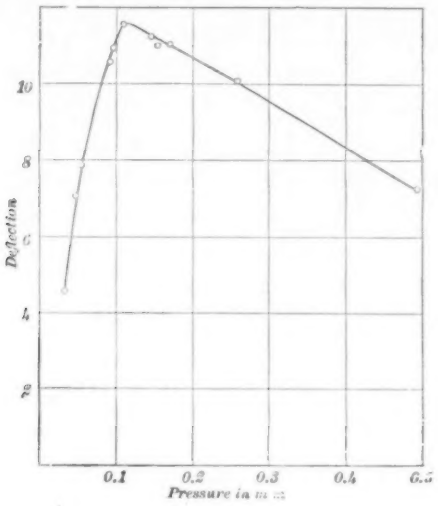


Fig. 4.

Ernest Nichols has found this maximum point to be about 0.05 mm., while our determination is about 0.1 mm. It is difficult to see how this difference can be accounted for in the construction of the radiometers. On the other hand, such a discrepancy might easily be due to the gauges themselves.

During the greater part of the experiment, I had no gauge at my disposal. This was of very little inconvenience as the period of vibration, and also the action of the valves in the pump served fairly well as methods of ascertaining the vacuum.

With suspension number two, an ordinary candle at a distance of 300 cm. gave a deflection of 103 mm. on a scale 63 cm. from the radiometer vanes. The instrument used by Nichols[1] in his recent work on star radiation, gave a deflection of 11 mm. on a scale 183 cm. from the mirror, the candle being 811 cm. distant. The radiomicrometer used by Boys in attempting to measure the radiation

[1] Ernest Nichols, Astrophys. Jl., Mch., 1901, p. 101.

from the stars, gave a deflection of 1.7 cm. under similar conditions. Computing our deflections under these same conditions, we have for number two 42 mm., and for number one, which was about four times as sensitive, 170 mm. But comparison should be made considering like areas of the surface exposed to radiation. When this is done, the sensitiveness of each instrument and suspension is as follows: Boys 0.9, Nichols 11, suspension number two 4 2, and suspension number one 17.

It must be remembered that it is not a very difficult matter to make a radiometer suspension more sensitive than any of these, but the difficulty lies in its use.

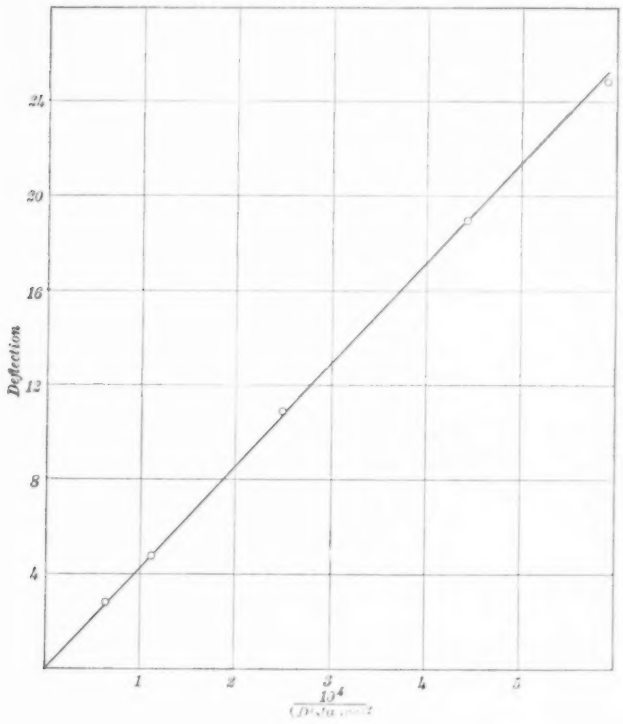


Fig. 5.

(*c*) *Accuracy.*—That the deflections of the radiometer are proportional to the energy when the vanes are 2 or 3 mm. from the window, has already been proven by Nichols. However, it

seemed desirable to make some sort of a test. I used the convenient method of observing the deflections produced by a constant source, placed at different distances. At first, results obtained in this way did not follow the inverse square law, varying as much as 15 or 20 per cent. The source, an acetylene flame, was constant to within much less than 1 per cent., and the large errors were due to the reflections from the walls of the room. The accompanying curve shows a series of observations made after various precautions were taken.

It will be noticed that, with one exception, the deviations from the mean are less than 2 per cent., and the character of these deviations show that with sufficient care a curve could be obtained which would agree with the inverse square law to within less than 1 per cent.

(*d*) *Difficulties.*—The advantage which the radiometer possesses over other devices for measuring radiant energy are well known, but as the instrument is somewhat new, the difficulties encountered with these sensitive adjustments will be mentioned in considerable detail.

1. The zero reading drifted almost constantly. The changes of temperature in the room, the lack of proper protection against the radiations from different parts of the room, the air draughts, and the lack of perfect symmetry in the construction of the vanes, tended to produce this effect.

The first of these causes could not be completely removed as the apparatus could not be conveniently set up in a constant temperature room.

The glass and fluorite windows were carefully shielded from all sources of radiation. It was found necessary to place a shutter in front of the glass window, and, with the more sensitive suspension, this shutter was opened only when taking a reading. Radiation from the room entering the top of the instrument caused no disturbances. In fact, a gas light several feet away and shining obliquely into the top seemed to have very little or no effect.

In the construction of the vanes care was taken to make them alike, but how nearly this was accomplished could not be learned as the construction of the instrument prevented such a test being made.

This drift of the zero of course affected the accuracy of the readings, but by taking the reading of the zero before and after each deflection, the error was less than one small scale division, and quite often less than one-fifth of this.

2. The annoyance which could be the least easily controlled, was the vibration of the suspension due to the tremor in its support. The entire apparatus was set upon a stone pier and this effect minimized as far as practicable. The tremor did not prevent the observer from reading the scale, but caused the suspension to vibrate over several small scale divisions. This effect seemed to be due to the large area and small inertia of the vanes, and the viscosity of the residual gas.

3. Throughout the experiment the radiometer was kept connected to the pump so that the vacuum could be changed at any time. Only twice did any trouble from leakage occur, and in both cases the trouble was located in the mercury-rubber seals. The radiometer itself would stand for weeks with practically no leakage. Even when in connection with the pump, at the end of a week the change in the vacuum would be less than 0.01 mm.

4. If the air were allowed to rush in or out of the radiometer too rapidly, the vanes would strike the mica window and become electrified. To prevent this, the rush of air was controlled by the pump stopcock, while the movement of the vanes was watched through the telescope.

Several methods of discharging the vanes were tried. The simplest and most successful was to permit the instrument to stand several hours in the open air, after first freeing the clinging vanes from the window. This electrification could be prevented by a little care, but, when it did occur, was a source of considerable annoyance.

5. In constructing a radiometer, the difficulties in using a suspension of long period should be borne in mind. In such a vibrating system, the moment of inertia is of small importance as compared with the viscosity of the gas, and so an effort must be made to make the area of the vanes as small as the work undertaken will permit. An improvement could have been made in our instrument by placing the slit closer to the vanes and making the vanes smaller. As in

many instruments, the accuracy is not proportional to its sensitiveness. For example, the sensitiveness of suspension number one was four times as great as suspension number two, yet its accuracy was not nearly so great in proportion, due to the fact that changes of temperature, air draughts, etc., produced a greater effect.

II. Observations in the Visible Spectrum.

The visible spectrum was explored previously to the employment of the device for the accurate setting of the sodium line upon the radiometer slit. The method here used consisted merely of adjusting until the reflection from the fluorite surface appeared the color of sodium light.

It was not supposed that this would give an accurate, but merely a consistent setting. Indeed, the average deviation from the mean of several adjustments was not more than 5″ on the spectrometer, or about 0.003μ. The later method showed that the adjustments made in this part of the experiment were in error by about 45″ toward the violet, or about 0.025μ. It was then a simple matter to correct the wave-lengths, no account being taken of the fact that the light did not pass through the prism at minimum deviation.

The source of light was a cylindrical acetylene flame from a single tip burner. This type was used because the intensity per unit area was greater than in the flat flame.

On account of the drift of the vanes, the zero was read before and after each deflection and the average taken in the computations. The time required for one deflection being five minutes, ten minutes was consumed in taking one reading.

The table below gives the results of the observations in the visible spectrum. The deflections recorded are averages of a large number of observations, taken with different degrees of sensitiveness, but reduced to similar conditions. They are about the actual size of the deflections which would be obtained with the most sensitive adjustment of suspension number one. The first column indicates the rotation of the prism table, the positive sign meaning a rotation toward longer waves. The points 0.800μ and 0.665μ were obtained from observations given under III.

TABLE I.

Angular Rotation.	Wave-Length.	Def.	Angular Rotation.	Wave-Length.	Def.
——	0.800μ	64.80	− 5′	0.460μ	.60
+4′	.710	28.60	− 8′	.415	.44
——	.665	16.25	−12′	.374	.44
+3′	.662	16.35	−15′	.352	.25
+2′	.620	8.90	−18′	——	.25
0′	.552	3.00	−21′	——	.25
−1′	.527	1.92	−25′	——	.17
−3′	.489	.97			

These data are plotted to a different scale in Fig. 6, curve 1. The deflections recorded between 0.3μ and 0.4μ are thought to be produced by diffused light. In the subsequent use of this curve, the

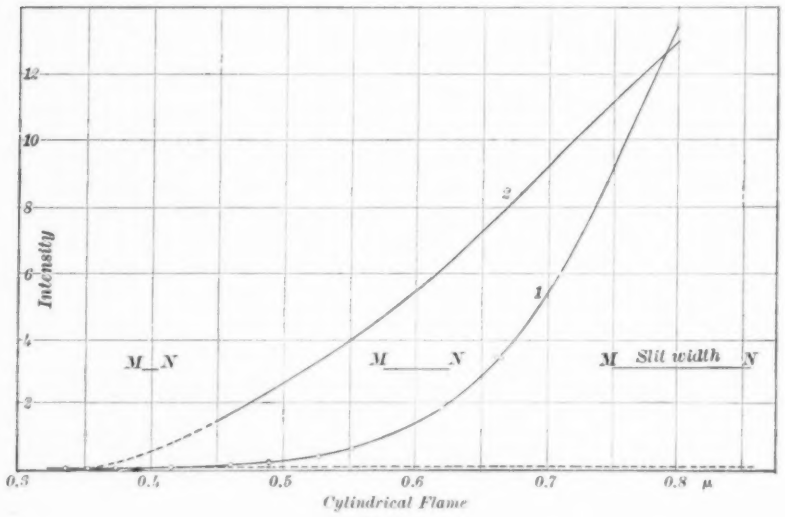


Fig. 6.

ordinate of the dotted horizontal line was considered as representing zero intensity.

Curve 2 is the result when proper corrections are made for slit widths. This method of correction will be explained under IV. The relation between the ordinates of any wave-length in the two curves has no significance, both being plotted to a convenient scale.

III. Observations in the Infra-Red.

1. Cylindrical Flame.

Owing to the difference in the dispersion of the prism, a slight change in the relative positions of the spectrometer and radiometer was of greater consequence in the infra-red than in the visible portion of the spectrum.

Correct results could be obtained only by making a series of observations in a small part of the spectrum and then checking back upon the sodium line. Many results had to be discarded because the relative position of the instruments had changed by an appreciable amount.

Table II.

	Wave Length.	Zero.	Reading.	Zero.	Def.
2′	0.665μ	41.75	39.50	41.61	2.18
4′	.775	41.28	33.92	41.20	7.32
5′	.855	40.80	29.40	40.69	11.35
6′	.952	40.50	24.81	40.38	15.63
7′	1.062	40.20	20.05	40.12	20.11
8′	1.196	39.85	19.00	39.80	20.82
9′	1.351	39.70	19.79	39.70	19.91
10′	1.504	39.70	21.31	39.80	18.44
[1]					
10′	1.504	39.97	21.59	40.00	18.40
11′	1.676	40.10	24.00	40.00	16.05
12′	1.847	39.90	26.02	39.90	13.88
13′	2.000	39.90	28.20	39.90	11.70
14′	2.140	39.90	30.20	39.90	9.70
15′	2.285	39.82	31.82	39.82	8.00
16′	2.419	39.70	33.69	39.80	6.06
17′	2.550	39.80	34.50	39.81	5.31
18′	2.664	39.81	34.53	39.79	5.27
19′	2.785	39.78	35.38	39.80	4.41
20′	2.904	39.80	36.10	39.80	3.70
[2]					
10′	1.504	39.78	21.50	39.71	18.25
[3]					
10′	1.504	39.50	21.05	39.30	18.35
20′	2.904	39.00	35.22	38.90	3.63
21′	3.012	38.80	35.80	38.70	2.95

[1] Here spectrometer was re-set on Na, and found 5″ in error.

[2] Returned to 10′.

[3] Spectrometer re-set on Na, and found 4″ in error.

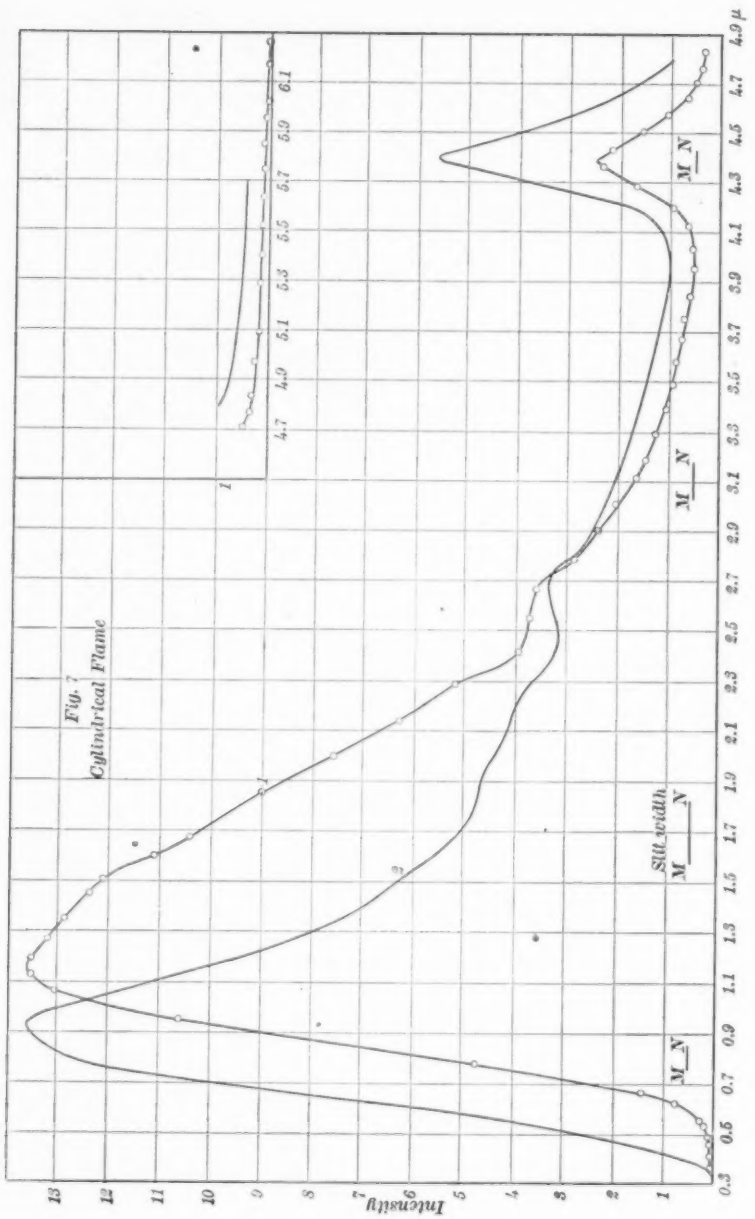


Fig. 7
Cylindrical Flame
Intensity
Slit width
M N
M N
M N
M N
1
2
4.7 4.9 5.1 5.3 5.5 5.7 5.9 6.1
0.3 0.5 0.7 0.9 1.1 1.3 1.5 1.7 1.9 2.1 2.3 2.5 2.7 2.9 3.1 3.3 3.5 3.7 3.9 4.1 4.3 4.5 4.7 4.9 μ
13 12 11 10 9 8 7 6 5 4 3 2 1

Fig. 7.

The preceding table, giving a series of observations covering a large part of the spectrum, shows the method used. The angles given in the first column signify the rotation of the prism table from the starting point, *i. e.*, the sodium line.

Curve 1, Fig. 7, obtained from this and other data, shows the distribution of energy as observed throughout the spectrum. It was useless to go any further than 6.0 μ, for readings beyond this region are perhaps false on account of diffused light. If all the observations taken were plotted, all the points would not lie upon this line, but the variation would not be 1 per cent. As an example of this variation, the maximum point, which is somewhat indefinite anyway, was found to shift only about 0.03 μ, from 1.14 μ to 1.17 μ. In an experiment of this sort, where the error due to the setting is so large in comparison with the errors in radiometer deflections, it is more satisfactory to draw a curve representing one series of observations carefully taken, than to draw an average curve. Curve 2 is the corrected curve which will be discussed under IV.

The most striking characteristic of curve 1 is the elevations which are due to the emission bands of the gases in the flame. If the acetylene is pure, the gases to be expected are CO_2 and H_2O.

Paschen[1] has made a study of the emission bands of both of these and has found the wave-lengths of the maxima under different conditions and temperature. He gives the following data for the bands found in the radiation from a bunsen burner.

H_2O SPECTRUM.

Maximum points, 1.46μ, 1.90μ and 2.83μ.

CO_2 SPECTRUM.

Maximum points, 2.71μ (2.68μ when CO_2 is not dry) and 4.40μ.

Although these values are computed from a dispersion curve different than the one used in our computations, yet the difference at the points considered would not be 0.01μ.

The energy curve shows elevations whose maxima agree very closely with these values, with the exception of the band 2.83μ

[1] Paschen, Annal. der Phys., 53, 1894, p. 334.

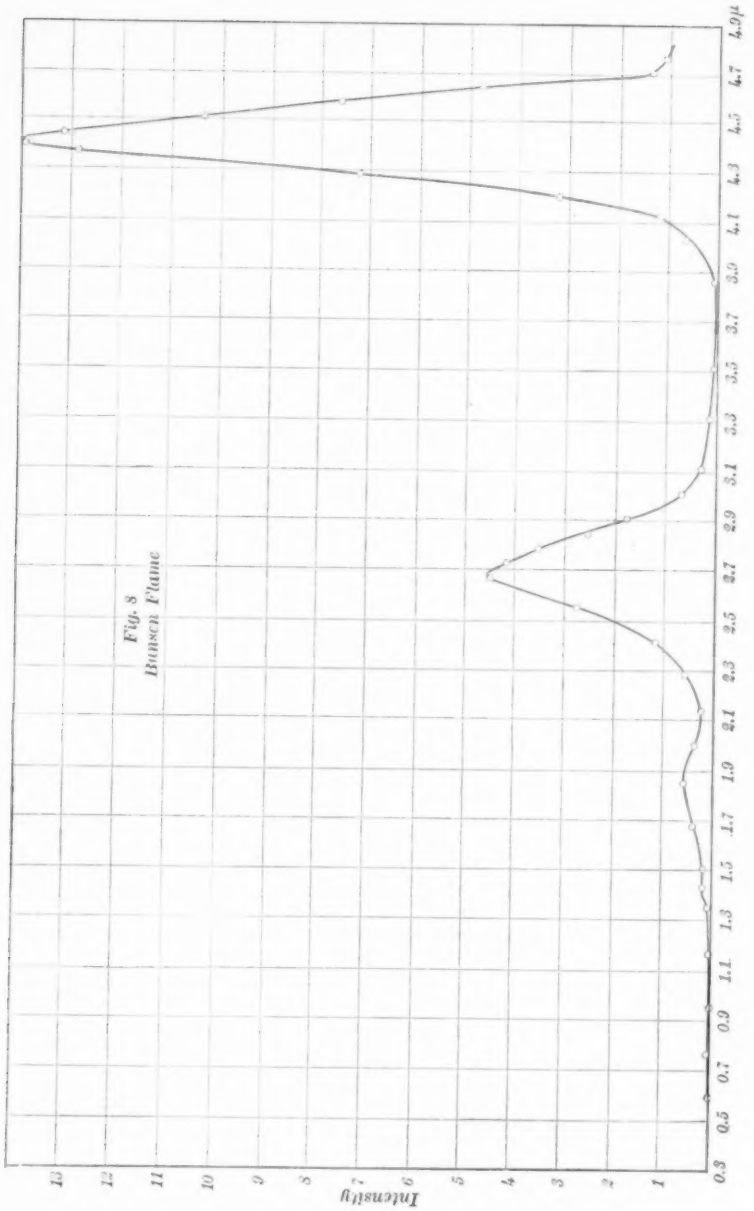


Fig. 8
Bunsen Flame
Intensity
15
12
11
10
9
8
7
6
5
4
3
2
1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
3.5
3.7
3.9
4.1
4.3
4.5
4.7
4.9μ

Fig. 8.

which is perhaps too small. By means of these points, we have an easy and accurate method of testing the spectrometer adjustment. The slight elevation at 2.3μ was obtained several times, and may be due to the emission of some impurity in the acetylene.

2. *Bunsen Flame.*

The curve for the acetylene bunsen flame is shown in Fig. 8. In this curve all five emission bands appear, and the values of the wave-length at the maximum points agree with the values quoted above. The bands being more distinct than in Fig. 7 we have still a better test for the adjustment of the apparatus. If we compare the bunsen and cylindrical flame curves, we see that they do not agree in all respects. The elevations due to the emission of the H_2O gas have not the same relative values in the two cases, but this discrepancy disappears when both curves are corrected for slit width. The band at 2.3μ does not appear in the bunsen flame, and this fact makes its presence in the other somewhat in doubt. That the apparatus permits only a very small amount of stray radiation, is well shown by this bunsen flame curve. In the neighborhood of 3.7μ the deflection is practically zero, while at 4.4μ it is very large.

3. *Flat Flame.*

Observations were next taken upon the flame of a two-jet Naphey burner. The relative positions of the flame and the spectrometer slit are shown in Fig. 9. The work upon the flat flame is not yet finished, the results obtained up to the present time, shown in Fig. 10, curve 1, being quite unsatisfactory. The lack of consistency in the observations is, in all probability, due to an unsteadiness in the flame itself. This might be due to the fact that the layer of burning gas is thin enough to be affected easily by air draughts.

Fig. 9.

The fact that the maximum with the Naphey burner is further toward the violet, is in agreement with the observations of Hartman,[1] who showed photometrically that the Naphey burner flame was

[1] E. L. Nichols, Journ. Frank. Inst., Nov., 1900.

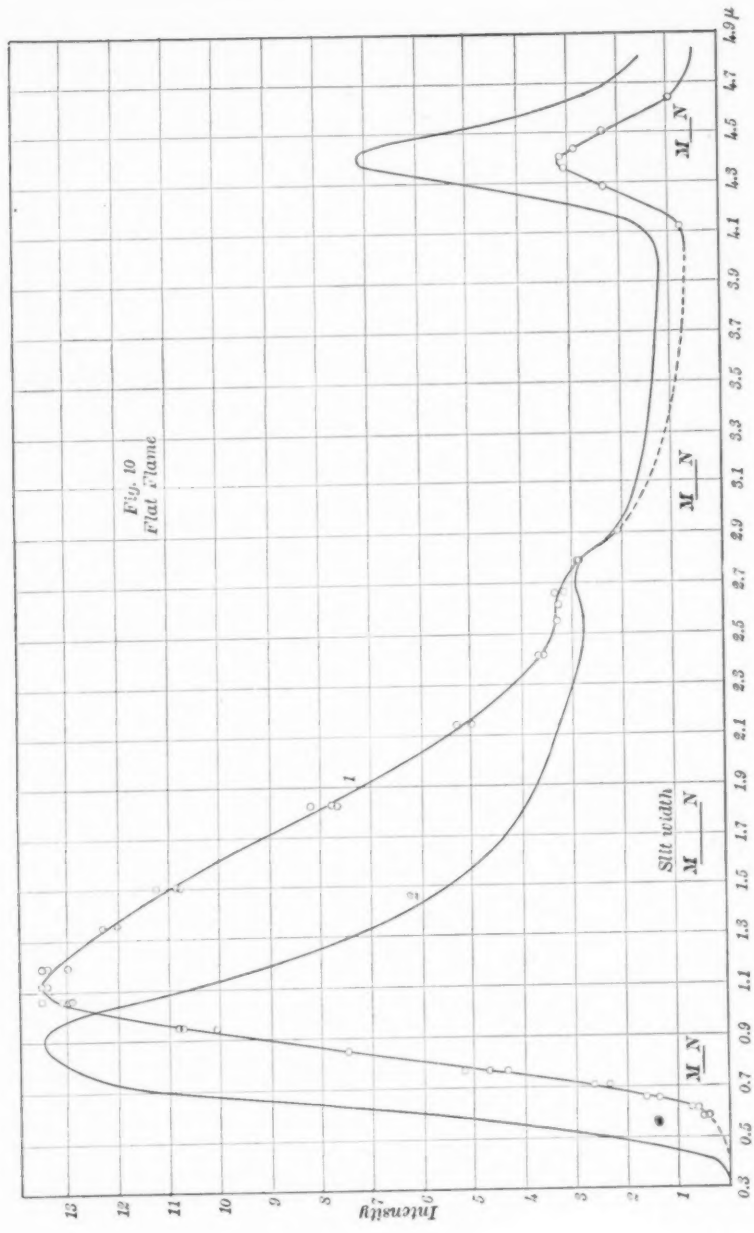


Fig. 10
Flat Flame
Slit width
M N
Intensity
0.3 0.5 0.7 0.9 1.1 1.3 1.5 1.7 1.9 2.1 2.3 2.5 2.7 2.9 3.1 3.3 3.5 3.7 3.9 4.1 4.3 4.5 4.7 4.9 μ
1 2 3 4 5 6 7 8 9 10 11 12 13

Fig. 10.

much richer in the violet. Curve 2 is the corrected curve and will be discussed later.

IV. Distribution in the Pure Normal Spectrum.

1. Slit Width Correction.

The curves of observations do not represent the actual distribution of energy in the pure spectrum. No matter how narrow the slit, a correction must always be made, for in such measurements we are concerned not so much with the actual as with the relative widths in the different parts of the spectrum. The method of this correction will be discussed in considerable detail, as there does not seem to be uniformity among the various writers who have had occasion to make such a correction.

When I first considered the matter, the following seemed to be an approximately correct method. Consider the spectrum falling upon the radiometer slit, or the spectrometer spectrum. In different parts of this spectrum the slit has different widths when expressed in wave-lengths, and if b and b' are the intensities in the spectrometer spectrum and a and a' the corresponding slit widths in wave-lengths, then the deflection obtained when the radiometer is at b is proportional to ab, and when at b', to $a'b'$. To find the distribution of energy in the spectrometer spectrum, we would then need only to divide the ordinates of the observed curve by the slit widths expressed in wave-lengths. But this spectrum is really composed of an infinite number of overlapping images of the spectrometer slit. Consider each wave-length to give such an image. Then at any point the number of overlapping images would be proportional to the width of the spectrometer slit expressed in wave-lengths. Hence, the intensity at any point in the spectrometer spectrum is proportional to the intensity in the pure spectrum and also to a, where a is the width of the spectrometer slit expressed in wave-lengths. Then to find the pure spectrum when the spectrometer spectrum is known, one has only to divide the intensities of the latter by a, a', etc. Combining these two steps, the slits being of equal width, the distribution of energy in the pure spectrum is obtained from the observed distribution by dividing the intensities of the latter by the square of the slit widths ex-

pressed in wave-lengths. This method is accurate only in so far as the pure spectrum curve may be considered a straight line for a length corresponding to a slit width.

Langley's[1] method of correcting for the bolometer strip width is, in effect, dividing the observed energy by the strip width in wave-lengths, and does not seem to take consideration of the spectrometer slit width.

Paschen[2] has given an accurate method of correction, taking into account both the strip width and spectrometer slit width. An approximation of his equation shows that he divides only by the slit or strip width, while on the other hand, Runge[3] in a later article, divides by the square of the slit width.

In recent articles on the radiation of black bodies, I find references to the method of Paschen and to the method of Runge, and one article refers to both as though they were the same. This is rather confusing. In my opinion Paschen is in error, and I shall repeat here part of his derivation of the equation to be used, at the same time making a correction.

In a pure spectrum, let $f(x)$ be the intensity per unit wave-length at the point x, where x is measured in wave-lengths. Let the radiometer slit or bolometer strip, and likewise the spectrometer slit, have a width a, where a is expressed in wave-lengths. If the radiometer slit is at x, then an image of the spectrometer slit due to the wave-length x will fall entirely within the radiometer slit, and the intensity of this image is $af(x)$. The intensity of the wave-length $x+v$ falling upon the radiometer slit at x is $(a-v)f(x+v)$. If $F(x)$ represents the total energy falling upon the radiometer slit, we then have,

$$F(x) = \int_0^a (a - v)[f(x + v) + f(x - v)]\,dv.$$

This differs from Paschen by the factor a. He says that the energy in the image of x is $f(x)$ and in the image of $x+v$ is $\frac{a-v}{a} f(x+v)$, and so his equation is

$$F(x) = \int_0^a \frac{a - v}{a} [f(x + v) + f(x - v)]\,dv.$$

[1] Langley, Phil. Mag., 17, 1884, p 184.
[2] Paschen, Annal. der Phys., 60, 1897, p. 712.
[3] Runge, Zeitschr. für Math. und Phys., 42, 1897, p. 205.

Making the change in his work, we have as a final equation,

$$a^2 f(x) = F(x) - \tfrac{1}{6}F_1(x) + \tfrac{2}{45}F_2(x) \cdots$$

where

$$F_1(x) = \frac{F(x+a) + F(x-a)}{2} - F(x)$$

and

$$F_2(x) = \frac{F_1(x+a) + F_1(x-a)}{2} - F_1(x).$$

I have used this equation in correcting the curves obtained from observations. $F_1(x)$ and $F_2(x)$ can be found graphically as explained by Paschen. $F(x)$ is observed, $F_1(x)$ determined from the curve of $F(x)$, and $F_2(x)$ determined from the curve of $F_1(x)$.

In my curves, the correction due to $F_2(x)$ was too small to be of any consequence, and so $f(x)$ was found simply by dividing $F(x) - \frac{1}{6}F_1(x)$ by the square of the slit width in wave-lengths. This slit width was determined from a curve showing the relation between wave-lengths and angular rotations of the prism table, and for the sake of greater accuracy, the values obtained were plotted with wave-lengths and a smooth curve drawn through these points.

2. *The Corrected Curves.*

This correction for slit width and impurity of the spectrometer spectrum would not be of great importance in parts of the spectrum where the dispersive power of the prism changes slightly, but in my curves, particularly in the visible portion of the spectrum, the corrected curve differs greatly from that observed. The absorption of the CO_2 and H_2O in the air between the source and the radiometer, make the observed curves very much in error at the points where we obtained emission bands. So the accurate method of correction was applied only from 0.4μ to 1.9μ and the remainder of the curve was obtained by dividing by the square of the slit width in wave-lengths.

In Fig. 7, it will be noticed that the maximum point has shifted from about 1.16μ on the observed curve, to about 0.93μ on the corrected one. Likewise in Fig. 10, the change has been from 1.12μ to 0.90μ. The observed maximum depends upon the values

of the energy in the pure spectrum and upon the slit widths in wave-lengths and should lie between the maxima of these two variables. This is verified, for the slit width has its maximum value at about 1.6μ.

A discrepancy in the relative intensities of the H_2O emission bands, 1.46μ and 1.90μ, in the curves of the bunsen and cylindrical flames, has already been mentioned. The bunsen shows that the band at 1.90μ is the more intense, and this is in agreement with the work done by Paschen. In the observed curve of the cylindrical flame, Fig. 7, curve 1, the opposite seems to be the case. However in the corrected curve, the band at 1.46μ scarcely shows, while the one at 1.90μ is quite distinct. The change brought about in the correction is due to the fact that the maximum value of the slit width is at about 1.6μ, and this has a tendency to exaggerate the elevation due to the band at 1.46μ.

3. *Temperature of the Acetylene Flame.*

The change in position of the maximum intensity in the spectrum of a black body with changes of temperature, is in agreement with the equation

$$\lambda_m T = A,$$

where λ_m is the wave-length of the maximum intensity, T the absolute temperature, and A a constant.

Lummer and Pringsheim[1] have found for A the value of 2940 and this agrees approximately with the results obtained by Paschen[2] and Mendenhall and Saunders.[3] Lummer and Pringsheim have also found the value of A to be 2630 in the case of bright platinum. They are of the opinion that the temperature of flames can be calculated from the formula, and that the true value for the temperature lies between the values obtained by assuming the two values for A.

Applying the formula, we obtain the following values:

CYLINDRICAL FLAME.

$\lambda_m = 0.93\,\mu$, $A = 2940$, $T = 3160°$, or about 2890° C.
$A = 2630$, $T = 2830°$, " " 2560° C.

[1] Lummer and Pringsheim, Verh. Deutsch. Phys. Gesell., 1899, p. 214.
[2] Paschen, Sitz. Kgl. Preuss. Akad. der Wiss. Ber., 1899, p. 959.
[3] Mendenhall and Saunders, Astrophys. Jl., Jan., 1901, p. 25.

FLAT FLAME,

$\lambda_m = 0.90\,\mu$, $A = 2940$, $T = 3270°$, or about 3000° C.
$A = 2630$, $T = 2920°$, " " 2650° C.

The temperature of the acetylene flame as determined by Nichols,[1] is about 1900° C. I am at a loss to understand the cause of the discrepancy in the application of this formula. The temperatures of different sources of light, calculated by Lummer and Pringsheim (loc. cit.) in a similar manner, are certainly more nearly within range of the correct values. A difference might arise in the method of correcting the observed curve. They say they reduce their curves to the normal spectrum, but fail to give the method. In a later article,[2] they state that when their curves were corrected according to the method of Runge, the resulting change was not more than 5 per cent.

Mendenhall and Saunders in the article already referred to say they have corrected their curves by dividing by $\frac{d\lambda}{d\delta}$ and that corrections were also made for the impurity of the spectrum according to Runge. It seems to the writer that these two methods are at variance, the one being in effect, dividing the observed values by the slit width in wave-lengths, while Runge divides by the square of the slit width in wave-lengths.

If calculations are made from our observed curves, the resulting temperature is yet about 100° C. too high.

It is quite possible that the value for A decreases with higher temperatures. Mendenhall and Saunders find a slight decrease, while Paschen finds an increase.

4. Radiant Efficiency.

In the study of devices for artificial lighting, the determination of the efficiency is of great importance, and to obtain this determination, the ratio of the radiation in the visible portion of the spectrum to the whole radiation, must be known. This ratio, or radiant efficiency, has already been determined for acetylene by Stewart

[1] E. L. Nichols, PHYS. REV., X., 1900, p. 234.
[2] Lummer and Pringsheim, Verh. Deutsch. Phys. Gesell., 1900, p. 163.

and Hoxie.[1] They used a modification of the Melloni method, and, from a large number of readings, obtained the value of 0.105 for the flat flame of a Naphey burner.

Langley was the first to utilize spectral energy curves for accurate determinations of the radiant efficiency. His method consisted in finding the ratio of the area in the visible portion of the spectrum to the area of the entire curve. My corrected curves were treated in this same manner, the visible spectrum being considered as ending at 0.76μ. The cylindrical flame curve, Fig. 7, curve 2, gave 0.100, and the flat flame curve, Fig. 10, curve 2, 0.131. I think there is no doubt but that the efficiency of the flat flame is the greater, but I do not place much reliance on the value 0.131, because the curve from which it was obtained is not satisfactory. The difference in the radiant efficiency of the two flames might be anticipated from the difference in temperature and color. If the absorption of the atmosphere were eliminated, these two values would be decreased by perhaps more than 0.01.

V. SOURCES OF ERROR.

1. The acetylene was made by the wet process and there was no attempt at purification. Mr. H. A. Rands made three analyses of the gas. The greater part of the acetylene was absorbed by fuming sulphuric acid, a solution of caustic potash removed the sulphur trioxide, oxygen was then removed with alkaline pyrogallol, and the remaining traces of acetylene were absorbed by cuprous chloride. He obtained 98.7, 98.4 and 99.0 as percentages of purity.

2. The gas coming from the reservoir passed through a pressure regulator devised by Prof. Moler.[2] Although several others were using gas at the same time, this device kept the pressure constant to within less than 1 per cent. Just how the variation in pressure would affect the energy entering the radiometer, depended not only upon the change in the flame itself, but also upon the position of the flame in regard to the spectrometer slit. It was found that if the pressure were changed 1 per cent., the change in the radiometer deflection would be only about 0.2 per cent.

[1] E. L. Nichols, PHYS. REV., XI., 1900, p. 215.
[2] E. L. Nichols, Journ. Frank. Inst., Nov., 1900.

3. Before reaching the radiometer vanes, the radiation from the acetylene flames passed through a fluorite prism, a fluorite plate and a very thin sheet of mica. The selective absorption of fluorite [1] does not begin until 6μ, and this is entirely out of our region. The mica being very thin, no appreciable absorption was to be expected. However, a test throughout the region in question was made, and this expectation verified.

4. The mirrors of the spectrometer, silvered according to Brashear's [2] method, were not highly polished. Such a surface causes diffused light and also makes the difference in percentage of reflection of the short and long waves greater than when the mirrors are highly polished. The diffused light was small, as can be seen from the visible spectrum curve, Fig. 6, and the bunsen curve, Fig. 8. Paschen [3] has recently shown that with a freshly silvered and highly polished mirror, the reflection at 0.7μ is 94 per cent. and at 6μ is 98 per cent., while in the case of a mirror four years old and having a distinct brownish tint, the reflection at 0.7μ is 85 per cent. and at 6μ is 95 per cent. Judging from these figures, it is probable that the reflection from our mirrors at these wave-lengths would differ by about 6 per cent. No attempt was made to correct the curves for this error.

5. The angle at which the radiation falls upon the face of the prism is different for different wave-lengths, and it is desirable to know how much error is made when this is not taken into consideration. Calculation by the Fresnel energy equation shows that when the radiometer is at 0.6μ, 3.2 per cent. is reflected, and when at 6.0μ, 2.7 per cent., a difference of only 0.5 per cent.

6. The percentage absorption of platinum-black for different wave-lengths is certainly different, and, moreover, is not known.

7. The absorption due to the presence of CO_2 and H_2O in the atmosphere of the room causes the curve to be in very great error at the emission bands of these gases.

8. In correcting the curves, only two terms of the series were used, but these approximated the true result within 0.2 or 0.3 at the point of greatest variation.

[1] Paschen, Annal. der Phys., 53, 1894, p. 812.
[2] Wadsworth, Astrophys. Jl., Vol. I., 1895, p. 252.
[3] Paschen, Annal. der Phys., 1901, p. 314.

If the errors 4 and 6 are not taken into consideration, I think the portion of the curve, Fig. 7, curve 1, between 0.7μ and 2.7μ is not in error by more than one per cent.

VI. Summary.

The distribution of energy in the spectrum of the acetylene flame is found in three cases by means of the spectrometer and the radiometer.

1. The cylindrical flame of a single-tip burner, distribution observed, Fig. 7, curve 1, actual distribution, curve 2, and the visible portion of the spectrum, Fig. 6, curves 1 and 2.

2. The flat flame of a two-jet Naphey burner, Fig. 10, curves 1 and 2.

3. Bunsen burner flame, Fig. 8.

These curves show the emission bands of H_2O and CO_2, and, the position of these bands being known, a check is had upon the adjustment of the apparatus.

The radiant efficiency of the cylindrical flame is found to be 0.100.

I wish to extend my thanks to Professors E. L. Nichols and Ernest Merritt, at whose suggestion and under whose direction the experimental work was performed.

The Physical Laboratory of Cornell University,
June, 1901.

TEMPORARY SET, AS ASSOCIATED WITH MAGNETOSTRICTION.

By Carl Barus.

Introduction.

In my earlier papers[1] on the subject, I inferred that the brilliant theories of magnetostriction due to Kirchoff, Korteweg, Lorberg, Helmholtz, Maxwell and others, can have but a limited application, inasmuch as the phenomena are inherently associated with what I venture to interpret as viscosity. In other words, if deformations evoked by physical changes of molecular configuration within the metal be termed viscous, *whether gradual or sudden*, then viscosity enters essentially into magnetostriction. With each twist, however small, and within the elastic limits the wire receives a certain amount of set, instantaneously; the whole of this set may be shaken out by the first magnetization and it is thus appropriately called temporary, to distinguish it from permanent set which comes much later, as a second phase lying beyond the limits of elasticity. On removing the magnetic field, therefore, the unmagnetic wire is molecularly different from the same unmagnetic wire before magnetization; and the new molecular arrangement is permanent so long as the twist is unchanged. Any change of twist, whether increment or decrement evokes new temporary set, or a new molecular grouping, which may be converted into the permanent grouping for the given twist, by a reapplication of the magnetic shake up in question. Hence throughout the whole period within which varying torsional stresses are applied, the metal is undergoing continual change of molecular constitution, which in relation to magnetostriction are as radical as though a new metal[2] were being continu-

[1] American Journal of Science, XXXIV., p. 175, 1887; X., p. 407, 1900; XI., p. 97, 1901.

[2] One may argue that the metal is not again normal until *after* the first magnetization. This is what I have done, virtually, and it works well: but one must acknowledge the ground debatable. At all events no fundamentally correct or physically acceptable theory will overlook the temporary set, which is just as much a part of magnetostriction as the elastic phenomena which follow.

ally supplied for investigation. These are the occurrences which a purely elastic theory does not adequately construe.

The gradual viscous deformations due to the heat motion within the wire are without bearing on the present experiments. They are of a different nature and easily eliminated.

The phenomena may then be analyzed as follows: Let a soft iron wire be subject to a fixed amount of torque, corresponding to a fixed amount of twist registered as a definite deflection (fiducial zero) on some appropriate scale. The first magnetization will produce (if twist is large enough) an increment of rigidity, registered as an increased deflection (say) on the scale. The withdrawal of the field does not reproduce the original deflection; the new deflection is in all cases smaller than the original deflection or below the fiducial zero; *i. e.*, the unmagnetic wire was virtually more rigid before than after the magnetization. If torque remains constant, the new conditions are persistent; so that on subsequent magnetizations the second deflection, on subsequent demagnetizations the third deflection, is regained almost perfectly. The inelastic feature has now been eliminated for the particular torque impressed. As the second deflection is eventually an increment, the third a decrement on the first, the elastic phenomenon is the numerical sum of both and is thus greater than either. There has been a slip of the fiducial zero favorable to greater deflection.

2. *Plan and Purpose.*—In the papers mentioned, more particularly in the last, I paid considerable attention to temporary set or *slip* as I then called it. It was found to be not very different (relatively) in the smallest (45°) and in the largest (360°) twists applied. Indeed between these limits of impressed stress, it seemed to pass through a maximum. Obviously, however, the slip must initially increase from zero with the twist. It is thus the chief purpose of the present paper to investigate the character and occurrence of temporary set for twists smaller than 45°, indefinitely. I shall moreover use a slightly different method of discussion, separating the increment of rigidity due to the first magnetization from the decrement of rigidity (slip) due to the first demagnetization for the purpose of discerning the nature of each.

In the interest of a definite scheme of investigation, the twists im-

parted should in some way regularly increase toward, or decrease from the highest values admissible. This is best accomplished by twisting the wire back and forth by amounts increasing in fixed steps and lying symmetrically on both sides of zero. In such a case the *antecedent* twist, *i. e.*, the total strain applied in any one direction since the last magnetization, will be the numerical sum of the positive twist and the negative twist from which the positive twist has been imparted; and vice versa. In other words, temporary set will here depend on an angle *different* from the impressed or actuating twist, while the increment of rigidity depends on the latter.

Again, if the wire is twisted in regularly increasing steps on one side of zero only, it should be brought back to zero for investigation between each twist. In this case the antecedent twist which determines the temporary set is the twist last impressed, while the actuating twist is zero.

What I make clear in this paper, is the dependence of temporary set or slip on the antecedent strain as above defined. Its direction is immaterial so far as the numerical amount of slip is concerned. The conditions under which slip is picked up by the magnetically increased rigidity in the presence of an impressed strain will also appear.

Throughout this paper in referring to magnetically increased rigidity I have in mind the simple torsion model described in an earlier paper.[1] When the wire is twisted the increment of tension along the lines of longitudinal stress due to magnetization, acts with a horizontal component in a direction equivalent to an increase of rigidity.

3. *Apparatus.*—This was the same differential apparatus heretofore described, consisting of identical upper and lower, collinear, vertical soft iron wires, joined in the middle by a light brass mirror support, and fastened at the ends to torsion heads. The upper wire was surrounded by a helix with internal water circulation. The two wires are countertwisted by the amounts θ each as given in the tables. The deflections occurring at the mirror when one wire is acted on magnetically, are observed on a centimeter scale 6 me-

[1] American Journ., X., p. 401, 1900.

ters distant. Thus 21 cm. of deflection correspond to one degree. The wires were each usually 37 cm. long and .044 cm. in diameter. The magnetic field of the long helix may be rated at about 100 c.g.s units per ampere.

The system of two wires was kept under a definite pull of about 300 grams, an insignificant amount. If the upper wire is twisted clockwise to an eye regarding it from above, an increased deflection denotes virtually increased rigidity of the upper (magnetized) wire.

This differential method was devised as has been stated elsewhere, to obtain direct relations between the deflection increments and the corresponding changes of rigidity. For if θ be the twist imparted to each wire, n their common original rigidity, if $d\theta$ and dn be the changes due to magnetostriction, then $n(\theta + d\theta) = (n + dn)(\theta - d\theta)$, seeing that the twist of the upper wire decreases by the same amount as the twist of the lower wire increases, while torque, length and section remain unchanged. Hence

$$dn/n = 2d\theta/\theta = \mu,$$

which I have called the coefficient of magnetically increased rigidity[1]. Its value is a definite minimum when the (elastic) obliquity of the external fiber is a maximum.

RESULTS FOR SUCCESSIVELY INCREASING ALTERNATING TWISTS.

4. *Preliminary.*—These results are given in the following tables, in which the first column shows the twist applied to each wire. The second to fifth columns show the reading at the scale in centimeters, originally (off (1)), and when the current is successively made and broken as the subscripts indicate. The sixth column gives the value of the antecedent twist, being the numerical sum of the existing and the preceding (opposite) twist. Great care must be taken not to exceed the strain limits stated, as otherwise the values of the antecedent twists stated would be quite erroneous. Accidents are noted. The 7th and 8th columns show the deflections from the original zero—off (1)—due to the first magnetization (on), and the first removal of the field. When these deflections have the same sign as the twist the rigidity of the magnetized wire

[1] American Journ., XXXIV., 1887, p. 181 et seq.

TABLE I.

Twists alternating symmetrically. Magnetic field, 380 *c.g.s. units. Soft iron; diameter* .044 *cm., length* 37 *cm., scale distance* 600 *cm., deflection* 21 *cm., equivalent to* 1°.

Twist of each Wire.	Scale Reading when Field is				Antecedent Strain.	Deflections[1] Referred to		
	Off (1)	On (1)	Off (2)	On (2)		Original Zero.		New Zero.
						On.	Off.	Total.
°	cm.	cm.	cm.	cm.	°	cm.	cm.	cm.
0					0			
− 5	0	+1.0	+1.5	+1.0	5	− 1	−1.5	.5
+ 5	0	− .5	−1.0	−1.5	10	− .5	−1	.5
−10	0	− .5	+1.0	0.0	15	.5	−1	1.5
+10	0	− .5	−1.0	− .5	20	− .5	1	.5
−20	0	.0	+1.8	.0	30	0	−1.8	1.8
+20	0	− .6	−2.2	− .6	40	− .6	−2.2	1.6
−30	0	− .4	+2.6	− .4	50	.4	−2.6	3.0
+30	0	.0	−2.4	.2	60	0	−2.4	2.4
−40	0	− .9	+3.0	− .8	70	.9	−3.0	3.9
+40	0	+ .6	−2.8	+ .6	80	.6	−2.8	3.4
−50	0	−1.6	+2.6	−1.6	90	1.6	−2.6	4.2
+50	0	+1.4	+3.1	+1.4	100	1.4	−3.1	4.5
0								
−50	0	−2.6	2.2	2.4	50	2.6	−2.2	4.8
+50	0	1.6	−2.6	1.6	100	1.6	−2.6	4.2
−60	0	−3.0	2.3	−2.8	110	3.0	−2.3	5.3
+60	0	2.2	−2.9	2.2	120	2.2	−2.9	5.1
−50	0	−1.4	2.9	−1.4	110	1.4	−2.9	4.3
+50	0	2.0	−2.6	2.0	100	2.0	−2.6	4.6
−40	0	− .4	3.2	− .4	90	.4	−3.2	3.6
+40	0	.8	−2.8	.8	80	.8	−2.8	3.6
−30	0	.4	3.1	.4	70	− .4	−3.1	2.7
+30	0	.0	−2.6	.1	60	.0	−2.6	2.6
−20	0	1.0	2.7	1.0	50	− .1	−2.7	1.7
+20	0	.0	−2.2	− .2	40	.0	−2.2	2.2
−10	0	1.0	2.0	1.0	30	−1.0	−2.0	1.0
+10	0	− .4	−1.2	− .3	20	− .4	−1.2	.8
− 5	0	.7	1.0	.8	15	− .7	−1.0	.3
+ 5	0	− .1	− .6	− .1	10	− .1	− .6	.5
0	0	.5	.5	.5	5	− .5	− .5	.0

is increased; for the case of opposite signs rigidity is decreased. The last column (numerical sum of the preceding two), shows the persistent or elastic increment of rigidity in the wire molecularly modified for the particular twist in question, as explained in paragraph 1.

[1] Taking the strains all positive, the deflections are changed in sign accordingly.

5. *Results.*—Omitting introductory experiments, results of a definite character are given in table 1, though the first few deflections taken but to centimeters, are too crude.

In the accompanying chart, Fig. 1, the deflections of the table are mapped out as ordinates relative to the given antecedent strains as abscissas, except in curve 3, where the impressed strains are the abscissas. The impressed strains are marked in degrees of arc on the peaks of the curves.

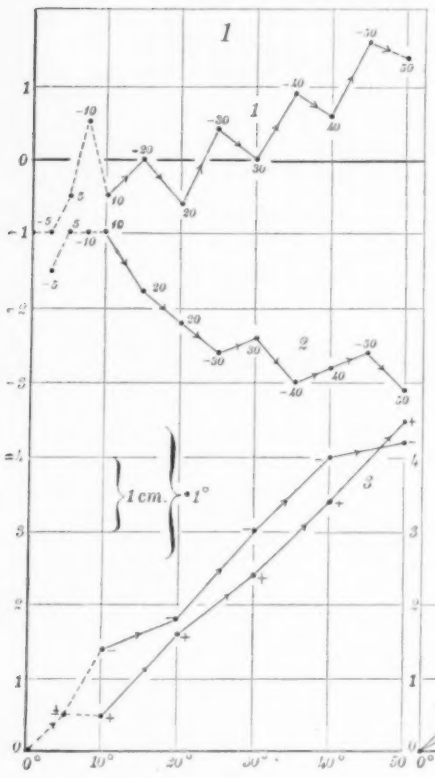


Fig. 1.

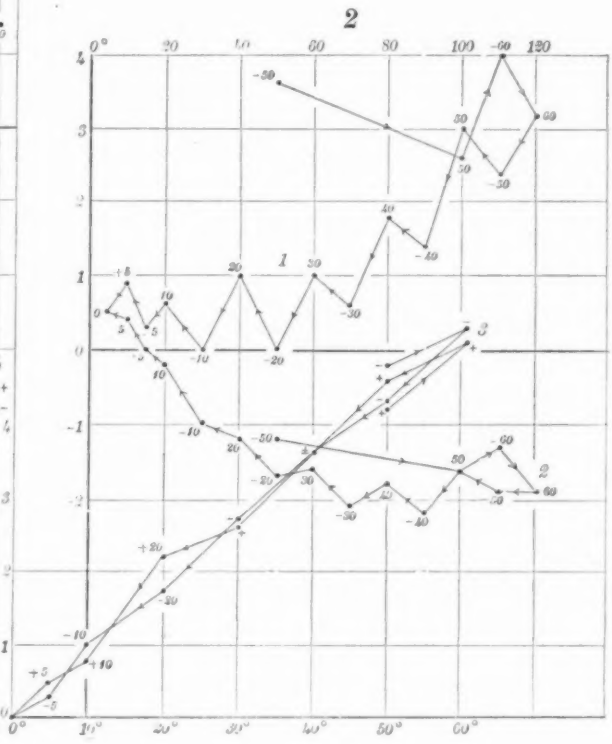


Fig. 2.

Curve 1 denotes the increase of rigidity due to the first magnetization relatively to the zero of the original unmagnetic wire. It shows the effect of temporary set or slip superposed on the effect of magnetically increased rigidity in the presence of the magnetic field and of the impressed strain stated. This curve is distinctly

alternating in character, like the twists. The rigidity is always *greater* for the *negative* twists with which the experiments begin, than for the positive twists of the same character which are subsequent.

As a whole, the mean increase of rigidity beginning with negative values is accelerated as twist increases. There is indication of a minimum.

Curve 2 shows the displacement (slip) of the fiducial zero of the unmagnetic metal before and after the first magnetization. It indicates the effect of slip in the presence of the impressed strain stated and of the magnetization, being the temporary set under these circumstances. Curve 2 corresponds definitely to a decrement of rigidity, which increases numerically with the twist but soon reaches a maximum at about $\pm 30°$ or $\pm 40°$ of impressed strain. The curve is much smoother than the preceding though it eventually runs into marked alternations. The initial slope is about

$$d\theta/\theta = .0026.$$

Curve 2 in connection with curve 1 shows that whereas the effect of slip is in excess for small strains, it is soon overtaken by the magnetically increased rigidity. *The alternations of both curves correspond in the main, but are opposed in phases.*

Curve 3, the algebraic difference of the two curves, shows the persistent magnetic increase of rigidity after the first magnetization. It represents the amount of magnetically increased rigidity in the absence of slip or temporary set for the impressed strain stated. The mean increment of rigidity is initially $dn/n = 2d\theta/\theta = .008$ for the positive twists and .0096 for the negative twists.

The second part of Table II. and the accompany chart (Fig. 2) contain corresponding results for a twist decreasing from 120° in successive steps of 10°. The curves are numbered as in the preceding chart.

Curve 1 has similar alternating characteristics to the preceding case; but the results are clearer throughout and they substantiate the occurrence of a minimum in the mean values for impressed twists of about $\pm 10°$ or $\pm 20°$. Beyond this, however, the curve presents a new result; the rigidities of the *positive* twists

are now successively in *excess* over the negative. The change of sign occurs at + 60° at the end of the curve.

TABLE II.

Twists alternating symmetrically. Magnetic field, 720 *c.g.s. Soft iron, diameter* .044, *length* 37 *cm. Scale distance* 600 *cm. Deflection,* 21° *cm. equivalent to* 1.

Twist of Each Wire.	Scale Reading for Field.				Antecedent Strain.	Deflections [1] Referred to		
	Off (1)	On (1)	Off (2)	On (2)		Original Zero.		New Zero.
						On	Off.	Total.
°	cm.	cm.	cm.	cm.	°	cm.	cm.	cm.
0					0			
− 5	0	− .2	.2	− .4	5	.2	− .2	.4
+ 5	0	0	.8	.0	10	0	− .8	.8
−10	0	− .2	1.0	− .2	15	.2	−1.0	1.2
+10	0	− .4	−1.6	− .4	20	− .4	−1.6	1.2
−20	0	− .2	1.9	0	30	.2	−1.9	2.1
+20	0	− .2	−2.8	− .2	40	− .2	−2.8	2.6
−30	0	− .8	2.4	− .8	50	.8	−2.4	3.2
+30	0	− .2	−3.2	.2	60	.2	−3.2	3.4
−40	0	−1.2	3.0	−1.1	70	1.2	−3.0	4.2
+40	0	1.0	−3.1	1.0	80	1.0	−3.1	4.1
−50	0	−2.8	2.2	2.8	90	2.8	−2.2	5.0
+50	0	−2.0	−3.0	2.0	100	2.0	−3.0	5.0
−40	0	−1.4	2.6	−1.3	90	1.4	−2.6	4.0
+40	0	1.0	−2.9	1.0	80	1.0	−2.9	3.9
−30	0	.2	3.3	.2	70	− .2	−3.3	3.1
+30	0	.1	−3.1	.1	60	.1	−3.1	3.2
−20	0	.8	2.9	1.0	50	− .8	−2.9	2.1
+20	0	− .4	−3.0	.4	40	− .4	−3.0	2.6
−10	0	1.0	2.2	1.0	30	−1.0	−2.2	1.2
+10	0	− .2	−1.6	− .2	20	− .2	−1.6	1.4
− 5	0	1.0	1.2	1.0	15	−1.0	−1.2	.2
+ 5	0	.6	− .4	.6	10	.6	− .4	1.0
0	0	.5[2]	.2	.5	5	.5	.2	.7

Curve 2 showing the temporary set under the given conditions is again a much smoother curve initially, indicating a decrement of rigidity with a limit reached at about ± 40°. Relatively to curve 1, slip is initially in excess, magnetically incremented rigidity even-

[1] Strains taken positive and signs of deflections changed accordingly.

[2] Zero at −7°, due to permanent set.

tually so, as before. The alternations of curves 1 and 2 correspond, but are now in the *same phase*. The initial slope is

$$d\theta/\theta = .003.$$

Curve 3 finally oscillates in irregular fashion about a straight line such that $dn/n = 2d\theta/\theta = .0088$, remembering that the abscissas here are actuating twists and not antecedent strains.

6. *Repetition of a Complete Cycle.*—The following cycles alternate in steps of 10° as far as ± 50°, but a stronger field of about 700 c.g.s. units is brought to bear. As a result the helix became warm, and gave rise to a permanent set of about 7°, the zero being found at −7° on unlocking the instrument, after completing the retrograde march.

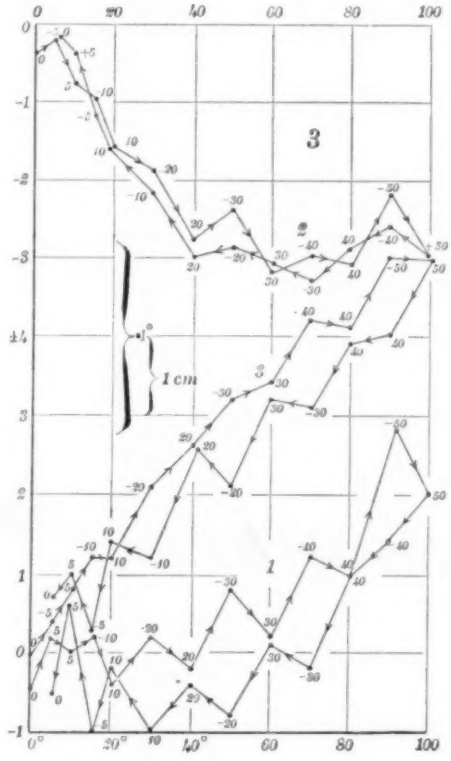


Fig. 3.

The results are given in Table II., following and constructed in in the chart Fig. 3, in the usual way. Curve 1 shows the effect of

the first magnetization referred to the original molecular status of the non-magnetic wire. Arrows indicate the progress of the experiment, which begins and ends at zero. The features of the preceding observations definitely reappear. The curve alternates with the twist; its mean value increases with the twist at an accelerated rate, passing from negative values, through a minimum at about 10°; in the outgoing march, the rigidity for the negative twists is greater than the rigidity of the corresponding positive twists; the reverse holds for the return curve. The curve of temporary set, 2, is again decremental in its two branches, and the march is definitely toward a limiting value at about ± 30° or ± 40°. It is smoother at first but oscillates markedly in the region of higher twists. The slope $d\theta/\theta = .0033$.

Finally both branches of curve 3, which shows the magnetically increased rigidity relatively to the new molecular status of the unmagnetic wire, are here given in terms of the antecedent strains as abscissas, merely for the sake of a clearer location of the observations. Relatively to the impressed twists (not shown) both branches may be described as oscillating irregularly about a straight line such that the corresponding elastic increment of rigidity is

$$dn/n = 2d\theta/\theta = .010.$$

The effect of doubling the magnetic field is thus not marked, for the slopes above (.0096 and .0088) are not much smaller, while the field was about half as large. Saturation may be assumed for both cases.

7. *Remarks in Explanation.*—The inferences of my earlier papers (l. c.) will be seen to be corroborated throughout and need not therefore be repeated. What is new, viz., the growth of different phases of the phenomena within ± 50°, has also been fully presented. With regard to slip, which reaches a limit at say ± 40° in the presence of impressed strain, it appears that after passing this value temporary set is more and more fully removed by the direct effect of magnetization, finally to fall off indefinitely.

The character of the curves 1, or the deflection produced on first magnetizing the non-magnetic metal in its original molecular status for the given twist, remains for explanation. The features of this

curve are its alternations, which are larger for a negative twist than for the succeeding positive twist of the same value in the outgoing series, with the reversed result in the return series; or vice versa. The peaks of the curves are of different sign in the advance and the retrogression, respectively. This observation is of considerable importance in its bearing on the present phenomena as will be seen in the sequel.

To account for the result it is at the outset sufficient to recognize (as already intimated) that the amount of temporary set or slip depends on the antecedent strain, whereas the increment of rigidity, caet. par., depends on the impressed strain or stress actually in action. Hence if a wire is twisted alternately in steps of $\pm\theta$ to a limit, and in like manner untwisted, the following series will determine the slip and the advance (incremented rigidity) due to the first magnetization of the original metal.

Slip due to Antecedent Strains.		Advance due to Impressed Strains.
θ		$-\theta$
2θ		$+\theta$
3θ		-2θ
4θ	Outgoing	$+2\theta$
$(2n-2)\theta$		$+(n-1)\theta$
$(2n-1)\theta$		$-n\theta$
$2n\theta$		$+n\theta$
$(2n-1)\theta$		$-(n-1)\theta$
$(2n-2)\theta$	Return	$+(n-1)\theta$
3θ		$-\theta$
2θ		$+\theta$
θ		zero

In the outgoing series, where the march of stress is increasing, the even antecedent twists are twice as large as the even (positive) impressed twists. In the odd twists, the former are always relatively less than this excess. Hence the slip in the even twists must be in excess of the slip in the odd twists, and thus the latter (negative) are given by peaks in the curve of rigidity, relatively to the valleys occupied by the former.

On returning the antecedent strains of the odd twists are the larger relatively to the corresponding (negative) twists in action. Hence the slip of the odd twists are relatively in excess and the even twists (positive) thus correspond to the peaks in the curve.

There can be no doubt that this explanation of the alternations of curve 1 is fundamentally correct. On closer inspection, however, an apparant discrepancy is revealed in relation to the curves 2. For whereas the increments of rigidity increase indefinitely with $n\theta$, the limit of curve 3 being as yet far off, the slips reach a minimum very early, as indicated by the curves 2 in question. One would therefore expect the oscillations of the curves 1 to cease at the same early limit.

A key to the situation is already given by the curves 2, which become markedly oscillating after the limit in question has been reached, while the character of these oscillations is reproduced and accentuated in the curves 1, either in the same or the opposite phase.[1] After passing $\pm 40°$ of impressed twist, the slip is picked up, as it were, by the concomitant advance of rigidity. Only a part of the total slip is manifest.

The probability of this state of things I have already put in evidence in the results of experiments in which slip in the absence of impressed strain was found to be a continually increasing quantity[2] even beyond 360°.

RESULTS FOR SUCCESSIVELY INCREASING, ASYMMETRICALLY ALTERNATING TWISTS.

8. *Results for Slip Alone.*—Before proceeding to further details, therefore, it is necessary to study temporary set in detail, under circumstances in which there is antecedent twist, but no impressed or acting twist. There must then be slip without the increment of rigidity. This may be done in accordance with the following scheme :

Slip due to Antecedent Strain.	Advance due to Impressed Strain.
θ	θ
θ	zero
2θ	2θ
2θ	zero

etc.,

in which for the even twists the wire is brought back to the unstrained state. In other words the wire is to be twisted successively

[1] The present discussion is in the main experimental and qualitative. A more detailed theoretical investigation will be given elsewhere.

[2] American Jour. of Science, XI., 1911, p. 105 et seq., §§ 8, 9.

TABLE III.

Twists alternating on one side of zero. Soft iron; diameter, .044, *length* 37 *cm. Scale distance* 600 *cm. Deflection* 21 *cm. equivalent to* 1°. *Magnetic field* 400 *c.g.s.*

Twist of Each Wire.	Scale Reading for Field.			Antecedent[1] Strain.	Deflection[1] Referred to		
					Original Zero.		New Zero
	Off (1)	On (1)	Off (2)		On.	Off.	Total.
°	cm.	cm.	cm.	°	cm.	cm.	cm.
+10	0	.2	− .8	10	Same	Same	1.0
0	0	.7	.7	10	as	as	0
20	0	.9	−1.1	20	column	column	2.0
0	0	1.3	1.3	20	3	4	0
30	0	1.1	−1.5	30			2.6
0	0	1.8	1.8	30			0
40	0	1.8	−2.0	40			3.8
0	0	2.6	2.6	40			0
50	0	3.0	−1.4	50			4.4
0	0	3.2	3.2	50			0
60	0	3.5	−1.7	60			5.2
0	0	3.8	3.8	60			0
70	0	4.2	−1.4	70			5.6
0	0	4.2	4.2	70			0
80	0	4.9	−1.2	80			6.1
0	0	4.6	4.6	80			0
90	0	5.2	−1.6	90			6.8
0	0	4.8	4.8	90			0
100	0	6.0	−1.2	100			7.2
0	0	9.2	——	100			0
90	0	5.5	−1.6	90			7.1
0	0	4.6	4.6	90			0
80	0	4.4	−2.0	80			6.4
0	0	4.4	4.4	80			0
70	0	4.1	−1.6	70			5.7
0	0	4.2	4.2	70			0
60	0	3.2	−1.8	60			5.0
0	0	3.6	3.6	60			0
50	0	2.8	−1.6	50			4.4
0	0	3.2	3.2	50			0
40	0	2.0	−1.9	40			3.9
0	0	2.6	2.6	40			0
30	0	1.5	−1.4	30			2.9
0	0	2.0	2.0	30			0
20	0	.8	−1.2	20			2.0
0	0	1.4	1.4	20			0
10	0	1.2	− .6	10			1.8
0	0	.8	.8	10			0

[1] All strains taken positive for simplicity and the deflections changed in sign accordingly.

to $n\theta$, magnetized during the action of the impressed torque with a record of the scale reading before and after magnetization; then untwisted and a similar record made. Results obtained in this manner are given in Table III. in the usual way. The table consists of two parts, of which the first is the outgoing series of increasing twists, each successively brought back to zero and the temporary

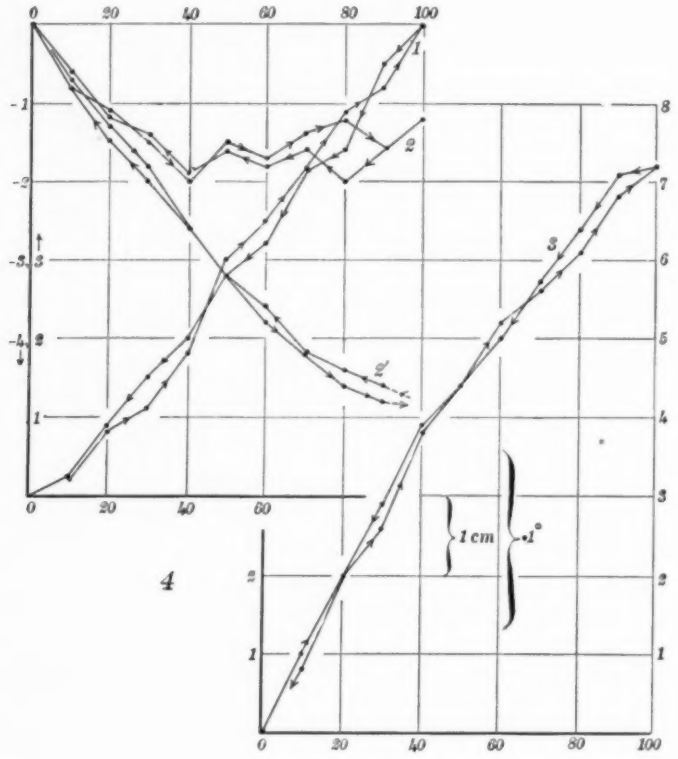


Fig. 4.

set shaken out by magnetization. The second part is the return series of corresponding data. The helix was provided with an internal water jacket to obviate changes of temperature, though continuous effects of this kind (ordinary viscosity) would be eliminated without this precaution. As a whole the two series are coincident, since the difference of a few millimeters in a scale distance of six meters can hardly be vouched for in experiments like the present,

where there is inevitably much manual interference in twisting and untwisting.

The graph (Fig. 4) for this table is constructed in the usual way, either the antecedent twists or the impressed twists being the abscissas and the deflections due to changes of rigidity, the ordinates. Curve 1 shows the superposed effect of slip and advance in the presence of magnetic field and of impressed strain, the notation following the above. The curve should be smooth; it is not quite so for reasons presently to be stated. There is a gap due to curtailed ordinates below 40° and resulting from excess of slip in this region. Above 40°, the mean line is nearly straight, and if prolonged backwards would nearly intersect the origin. The slope $dn/n = 2d\theta/\theta = .003$. Direct and return curves are practically identical. The curve shows a radical departure from the corresponding case (1) in Fig. 3, as predicted.

In curve 2, showing the temporary set in the presence of the impressed strain stated, the oscillations begin markedly at about 40°, as usual, in spite of the totally new schedule of operations. The alternations of curve 1 are imaged in the same phase with accentuation throughout, the reverse having been the case above. The direct and retrograde curves are not coincident throughout. The slope is about $d\theta/\theta = .003$.

Curve 2′ is the specially new feature of the present experiments. It shows the amount of temporary set or slip for any antecedent strain in the absence of impressed strain. The smooth curve obtained in this case, practically coincident in the outgoing and the return branches, is evidence of the truth of the inferences expressed in the last paragraph. The curve also comes to a limit eventually, but the limit is considerably beyond the limits of observation. When contrasted with curve 2, the difference in ordinates shows the amount of slip *picked up* by the magnetically incremented rigidity, for any angle of twist. The initial slopes of 2 and 2′ are about identical, $d\theta/\theta = .003$, having about the same value with the sign changed as in curve 1. This curious feature is noteworthy as it occurs again below.

Curve 3 has the usual meaning, being the advance due to the magnetically increased rigidity in the absence of slip. The initial

coefficient here is about $dn/n = 2d\theta/\theta = .0092$, the usual value. The curve happens to consist of two nearly linear parts, one between 0° and 40°, the other between 40° and 90°, corresponding to the oscillations of curve 2.

Looking over the whole series of phenomena, one derives the impression that the effects are not quite statistical, *i. e.*, that the number of molecules immediately engaged are not so numerous as in the kinetic theory of gases, for instance, and that for this reason the phenomena fall short of obedience to sharp laws. Sufficient variation was made in the apparatus to throw out errors due to it; but whether the mechanical interference which must inevitably accompany these experiments will not also shake out temporary set, remains to be seen.

TABLE IV.

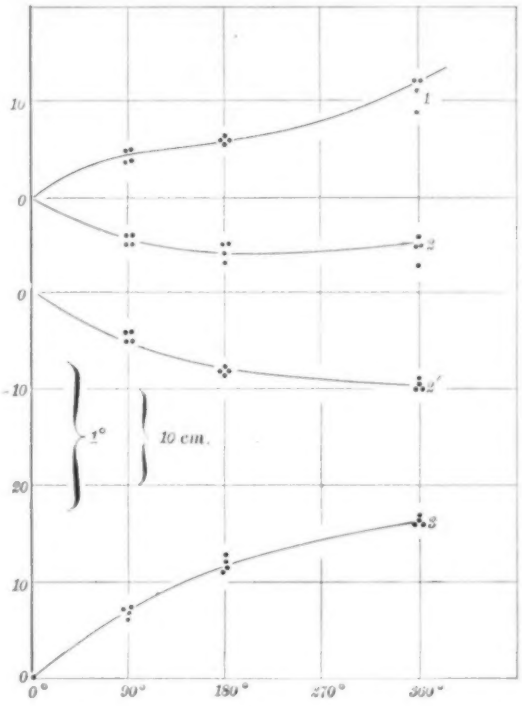
Twists alternating on one side of zero. Magnetic field 800 *c.g.s., soft iron, diameter* .024, *length* 35 *cm., scale distance* 500 *cm.,* 18 *cm. equivalent to* 1°, *nearly.*

Twist of each Wire.	Scale Reading when Field is			Antecedent Strain.[1]	Total Deflection.[1]
	Off (1)	On (1)	Off (2)		
°	cm.	cm.	cm.	°	cm.
−360	0	9	− 7	360	16
0	0	9	9	"	0
+360	0	−11	5	"	16
0	0	−10	−10	"	0
−360	0	12	− 4	"	16
0	0	10	10	"	0
+360	0	−12	5	"	17
0	0	−10	−10	"	0
−180	0	6	− 6	180	12
0	0	8	8	"	0
+180	0	− 6	7	"	13
0	0	− 8	− 8	"	0
−180	0	6	− 5	"	11
0	0	8	8	"	0
+180	0	− 6	5	"	11
0	0	− 8	− 8	"	0
− 90	0	2	− 5	90	7
0	0	5	5	"	0
+ 90	0	− 3	4	"	7
0	0	− 5	− 5	"	0
− 90	0	2	− 5	"	7
0	0	5	5	"	0
+ 90	0	− 2	4	"	6
0	0	− 6	0	"	0

[1] Strain taken positive for simplicity and deflections changed in sign accordingly.

9. *Case of Larger Twists. Thin Wire.*—The following data for a thinner wire are taken from my earlier work where they occur in a different connection and without being numerically stated. Readings were made to centimeters, not to millimeters as above; but the wire being thinner, showed correspondingly larger deflections.

One may note that while the total deflection (increment of rigidity in the absence of slip) remains nearly constant for any twist, the ratio of the component slip and advance implied may change in marked degree. This is particularly noticeable for the twist of 360°.



5
Fig. 5.

The graphs, Fig. 5, are numbered as in the preceding chart. Remembering that, in view of smaller diameters (.024 cm.), the twists here are relatively greater, results corroborating the preceding paragraph may be deduced. Curve 2 reaches a limit much before curve 2′, the difference being the slip picked up during

magnetization by the coincident increment of rigidity. The initial slopes of curves 1 and 2 ($d\theta/\theta = .003$), are nearly equal and opposite; the initial slopes of 2 and 2′ nearly identical, showing the paramount *initial* (vanishing twists) importance of slip. Curve 3 and curve 2′ show similar contour, indicating close relation of slip and advance. The former is throughout numerically somewhat less than twice the latter, in ordinate. Initially, at least, the effect of magnetization may be conceived to be expended in producing slip and advance in the ratio of 1 : 2, though necessarily in opposed directions.

In Table IV. many alternations were made consecutively for each twist selected. This method does not lend itself well for the present purposes where a continuous record is wanted. Hence the following data were investigated.

TABLE V.

Twists alternating on one side of zero. Magnetic field 400 *c.g.s., soft iron, diameter* .044, *length* 37 *cm., scale distance* 600 *cm., deflection* 21 *cm., equivalent to* 1°.

Twist of each Wire.	Scale Reading for Field.			An ecedent Strain.[1]	Total Elastic Deflection.[1]
	Off (1)	On (1)	Off (1)		
°	cm.	cm.	cm.	°	cm.
45	0	2.2	−1.8	45	4.0
0	0	3.5	3.5	"	0
90	0	5.1	−1.3	90	6.3
0	0	4.6	4.6	"	0
135	0	7.3	−1.1	135	8.4
0	0	5.6	5.6	"	0
180	0	8.6	− .8	180	9.4
0	0	5.8	5.8	"	0
225	0	9.4 10.0	− .2	225[2]	9.6 10.2
0	0	5.6	5.8	"	−.2
180	0	8.6	− .9	180	9.5
0	0	4.9	5.1	"	−.2
135	0	7.0	− .9	135	7.9
0	0	4.8	5.1	"	−.3
90	0	4.9	−1.7	90	6.6
0	0	4.3	4.5	"	−.2
45	0	1.6	−2.0	45	3.6
0	0	2.4	2.6	"	−.2

[1] Strains taken positive and deflections changed in sign accordingly.

[2] Permanent set occurs here. After final unlocking, the zero was at —33 cm., being a set of 1.6°.

10. *Case of Larger Twists. Thicker Wire.*—The observations of Table V. were made for the same diameter and length of soft iron

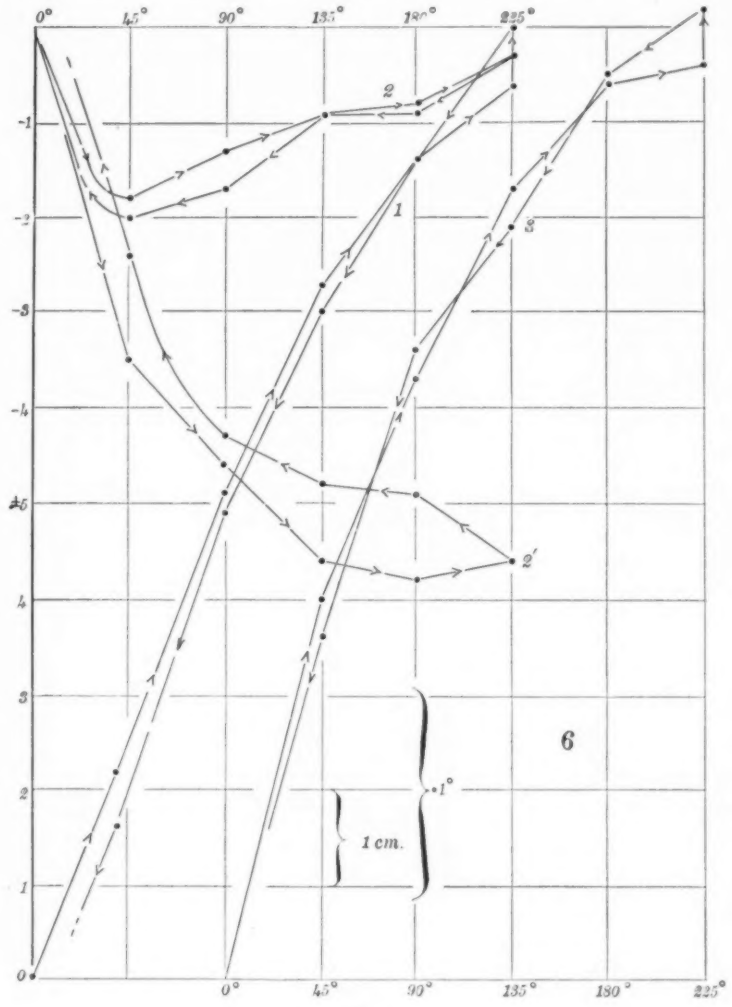


Fig. 6.

wire occurring throughout the bulk of the above experiments. It being the object to proceed quite up to the limits of elasticity, twists exceeding 200° were necessary, and the data are given in the following table containing both an outgoing series and a return therefrom. The inevitable occurrence of permanent set here before 225° is reached, interferes with coincidence between the two series.

The results are given in the accompanying graph, Fig. 6, in the usual way, the abscissas being either antecedent strains or impressed strains as required. Curve 2′ shows the temporary set in the absence of impressed strain, curve 3 the advance due to magnetically increased rigidity in the absence of slip. In curve 1 there is superposed slip and advance in the presence of impressed strain and of magnetization. In curve 2, slip in the presence of impressed strain but absence of magnetization.

The smoothness of curve 1 is marked except at the end, where after the occurrence of *permanent* set, the direct and return curves are shifted laterally about 1 or 2 degrees relatively to each other. The initial slope is $d\theta/\theta = .0026$, somewhat smaller than above, but the initial curve is not so near the initial tangent. Greater smoothness corresponds to less interference, since the steps are 45°. In other respects curve 1 contains but little new information.

The case of curve 2, however, presents novelties. The above sharp minimum at about 40° is substantiated, after which the curve in its progress toward 225° nearly falls off to a vanishing deflection in the region of permanent set. The meandering path between 40° and 100° is again suggested by the new curve. The initial slope practically coincides with 2′.

Similarly definite results are obtained from curve 2′, showing the occurrence of slip alone in the absence of impressed strain. Temporary set reaches a definite limit at about 200°, after which there is *unstable* molecular equilibrium merging into permanent set. This lapse into a new and permanent molecular grouping which cannot again be transferred back by the magnetic shake-up, is the reason for divergence in the outgoing and the return series. The whole of the temporary set does not vanish, however, a natural result seeing that the yield in a practical case is always local and not distributed throughout the wire. The slope here is about $d\theta/\theta = .0037$, but it is not the initial tangent.

Curve 3, finally with an initial slope corresponding to

$$dn/n = 2d\theta/\theta = .0082,$$

which naturally falls short of the above value, rises to a definite limit with the occurrence of set. If this were obviated by much

twisting, the limit would be more remote as is known from the earlier experiments.

11. *Conclusion and Summary.*—Before proceeding to definite statements it is expedient to reduce all data to common torsion standards. In my earlier work[1] the obliquity (ω radians) of the external fiber was found to be convenient for reference, while all twists were expressed (in rates $\tau°$) per unit of length. This to some extent eliminates the arbitrary lengths and radii involved. If the twist of each wire is $\theta°$, $\tau = \theta/l$, where l is the length of the wire of radius r. Moreover $\omega = \pi r\theta/180 \times l = \pi r\tau/180$.

For the two lengths and diameters occurring ($2r = .044$, $l = 37$ cm., and $2r = .024$, $l = 35$ cm.), the constants, are therefore, $\omega = 10 \times \theta/10^6$ nearly, and $\omega = 26 \times \theta/10^6$. Thus the limits of temporary set (curves 2′) in the cases of Tables IV. and V. occur at $\omega = .0022$ and $\omega = .0020$ radians, which are practically the same. In my old results operating with curve 3, permanent set occurred when $\omega = .003$ radians; but here the limit was pushed to the utmost verge by hardening the locally weak places by continued twisting. It is understood that ω refers to elastic deformations, no matter how much permanent set may have been previously imparted.

The minimum of curve 2, for temporary set in the presence of impressed strain and evoked by magnetization occurs for $\omega = .0004$ radians in case of Table V. In Table IV. the steps are too large, so that it can be merely located below $\omega = .0008$ radians.

The chief result of the present paper is the detection of the growth conditions of temporary set, a latent strain distinguished from permanent set in that the former may be shaken out of the soft iron wire by molecular agitation. Temporary set $d\theta$ is an instantaneous accompaniment of any twist within the elastic limits; it begins with the zero of twist at an initial rate of about $d\theta/\theta = .0037$, increasing at a retarded rate to a superior limit when the (elastic) obliquity of the external fiber exceeds .002 radians. After this the wire begins to yield locally, gradually, acquiring permanent set. The new molecular condition is stable and can not be shaken out. In soft iron temporary set is made mani-

[1] American Jour., XXXIV., p. 182, et seq.

fest as a slip in the absence of impressed strain on instantly applying a magnetic field following an antecedent strain. The limiting amount of temporary set which can be stored may be estimated as .0015 of the limiting twist within the elastic limits.

In the presence of impressed strain, a longitudinal magnetic field produces both magnetically increased rigidity and temporary set, as superposed phenomena. For small twists θ the rate is $d\theta/\theta = .003$ and positive. For larger angles the increase is gradually retarded but continues until permanent set is definitely established. Thus magnetically increased rigidity supervenes throughout, being initially about twice the slip. When the antecedent twist differs from the impressed twist, slip is to be associated with the former and advance with the latter and the statement of the result requires a detailed analysis. Cf. §§ 4–7.

The slip in these instances is initially quite as large as in the absence of impressed strain, the initial coefficient being $d\theta/\theta = .0035$. It soon, however, reaches a pronounced minimum (algebraically), showing that slip is more and more arrested or picked up by the concomitant magnetically increased rigidity, until with the occurrence of permanent set, slip (evoked by magnetization in the presence of impressed strain) has all but vanished. The minimum in question is determined by $\omega = .0004$ to .0008, while permanent set does not occur until $\omega = .002$ to .003.

Finally magnetically increased rigidity in the necessary presence of impressed strain and the absence of slip increases with the impressed twist at an initial rate of $d\theta/\theta = .0046$. The coefficient of rigidity is thus of the order of $\mu = dn/n = .01$. As the twist increases the coefficient μ decreases to a limit of about .004, when ω exceeds .002, elastically. If the wire is hardened by indefinite twisting beyond the elastic limits, μ seems to approach a lower limit when ω is elastically .003. In my old results I thus found

$$\mu = .002$$

in a field of about 140 c.g.s. units and a large range of diameters (.2 to .02 cm.). Mr. H. D. Day[1] showed that the limit of μ in

[1] Day, American Journ. Sci., III., 1897, p. 449. Cf. p. 456.

very strong fields has not been reached, finding $\mu = .003, .005, .006$, in fields of 100, 500 and 1,500 c.g.s. units, respectively.

The energy stored and eventually wasted in temporary set may be of passing interest. Since this work is half the product of the stress and the strain given by curves $2'$, it appears that in case of Table V. ($2r = .044$) when slip has its largest value ($.27°$), this work does not exceed 300 ergs. Since the ratios of this work done in twisting and the energy wasted in slip are as the squares of the angles of twist and slip, about $2.4/10^6$ of the work done in twisting is lost in producing temporary set when the latter is at its maximum value just within the elastic limits. Initially the relative waste is much greater, being the square of the initial slope, $d\theta/\theta$, of curve $2'$; *i. e.*, the waste is $(.0037)^2 = 14/10^6$, nearly.

The case of Table IV. hardly contains sufficiently detailed data. About 100 ergs would be stored up when the slip is at a maximum ($.51°$) just within the elastic limits. The corresponding final waste ratio would be but $.4/10^6$. The initial waste ratio is

$$(.0033)^2 = 11/10^6,$$

about of the same order as in the preceding case.

The energy wasted in magnetic hysteresis in double reversals per cubic cm. of saturated soft iron is about 10,000 ergs. Comparing this with the energy wasted in temporary set, Table V. shows that $300/\pi r^2 l = 1,300$ would be wasted per cubic cm., and for a double reversal therefore 2,600 ergs.

From Table IV. it appears that $100/\pi r^2 l = 1,590$, or about 3,200 ergs in a double reversal.

Seeing that it is somewhat difficult to get parallel cases for comparison, it will be noticed that the energy dissipated in a double reversal and saturated soft iron, magnetically in the one case, and mechanically in the other, is of a common order of values; for temporary set must be compared with residual magnetization.

Apart from its inherent importance as an introductory phase of permanent set, temporary set has therefore the additional interest of being a clearcut instance of purely mechanical hysteresis, *without* necessary relation to magnetism, as I understand it. To further establish this it will eventually be necessary to invent means to

detect temporary set in other and non-magnetic metals. It follows moreover that the Weber-Ewing model of revoluble molecular magnets is either not the final resource for the physical explanation of magnetism, or else that its polar properties have a much wider application than simply to magnetic phenomena. On the whole the analogy of temporary set with magnetization is attractive; magnetization may be shaken out of soft iron by mechanical tapping; similarly temporary may set be shaken out by magnetization, etc. In addition to the intimate connection of temporary set and magnetic hysteresis, it is also probable that the same slip lies at the root of Kelvin's "fatigue of elasticity," as yet an unclassified phenomenon in the domain of viscosity.

BROWN UNIVERSITY, PROVIDENCE, R. I.

A PRELIMINARY COMMUNICATION ON THE PRESSURE OF HEAT AND LIGHT RADIATION.

By E. F. Nichols and G. F. Hull.

MAXWELL,[1] dealing mathematically with the stresses in an electro-magnetic field, reached the conclusion that "in a medium in which waves are propagated there is a pressure normal to the waves and numerically equal to the energy in unit volume." Bartoli,[2] in 1876, announced that the existence of such a stress was essential to the validity of the second law of thermodynamics. He sought for such a pressure experimentally but failed to get conclusive results. The problem has been discussed theoretically, on the basis of thermodynamics, by Boltzmann[3] and by Galitzine.[4] Lebedew[5] applies such a pressure, opposed to the sun's gravitation, to account for the solar repulsion of comets' tails; and more recently Arrhenius[6] attempts to explain the aurora borealis on similar grounds.

Every approach to the experimental solution of the problem has hitherto been balked by the disturbing action of gases which it is impossible to remove entirely from the space surrounding the body upon which the radiation falls. The forces of attraction or repulsion, due to the action of gas molecules, are functions of the temperature difference between the body and its surroundings, caused by the absorption by the body of a portion of the rays which fall

[1] J. C. Maxwell, Elec. & Mag., 1st Ed., Oxford, 1873, Vol. 2, p. 391; also 2d Ed., Oxford, 1876, Vol. 2, p. 401.

[2] S. Bartoli, Sopra i movimenti prodotti della luce e dal calore: Florence, Le Monnier, 1876; also Exner's Repert d. Phys., 21, p. 198. 1885.

[3] L. Boltzmann, Wied. Ann., 22, p. 31; also p. 291; also Wied. Ann., 31, p. 139.

[4] B. Galitzine, Wied. Ann., 47, p. 479, 1892; also Phil. Mag., 85, p. 113, 1893.

[5] P. Lebedew, Wied. Ann., 45, p. 292, 1892.

[6] S. Arrhenius, Konigl. Vetanskaps-Akademiens, Förhandlingar, 1900; also Phys. Zeitschrift, Nov. 10 and 17, 1900.

upon it, and of the pressure of the gas surrounding the illuminated body. In the particular form of apparatus used in the present study the latter function appears very complicated, and certain peculiarities of the gas action remain inexplicable upon the basis of any simple group of assumptions which the writers have so far been able to make.

Since we can neither do away entirely with the gas nor calculate its effect under varying conditions, the only hopeful approach which remains is to devise apparatus and methods of observation which will reduce the errors due to gas action to a minimum. There are four ways in which the partial elimination of the gas action may be accomplished experimentally:

1. The surfaces which receive the radiation, the pressure of which is to be measured, should be as perfect reflectors as possible. This will reduce the gas action by making the rise of temperature due to absorption small while the radiation pressure will be increased; the theory requiring that a beam, totally reflected, exert twice the pressure of an equal beam completely absorbed.

2. By studying the action of a beam of constant intensity upon the same surface surrounded by air at different pressures, certain pressures may be found where the gas action is smaller than at others.

3. The apparatus—some sort of torsion balance—should carry two surfaces symmetrically placed with reference to the rotation axis, and the surfaces on the two arms should be as nearly equal as possible in every respect save one—the forces due to radiation and gas action should have the same sign on one side and opposite signs on the other. In this way a mean of the resultant forces on the two sides should be, in part at least, free from gas action.

4. Radiation pressure, from its nature, must reach its maximum value instantly, while observation has shown that the gas action begins at zero and increases with length of exposure, rising rapidly at first, then more slowly to its maximum effect, which, in most of the cases observed, was not reached until the exposure had lasted from 2½ to 3 minutes. For large gas pressures an even longer exposure was necessary to reach stationary conditions. The gas action may be thus still further reduced by a ballistic or semi-ballistic method of measurement.

The Torsion Balance.

The form of suspension of the torsion balance, used to measure radiation pressure in the present study, is seen in Fig. 1. The ro-

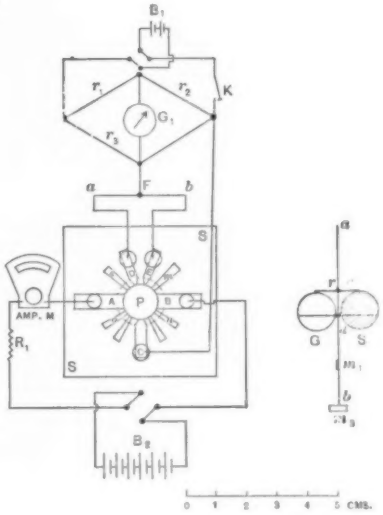


Fig. 4.

Fig. 1.

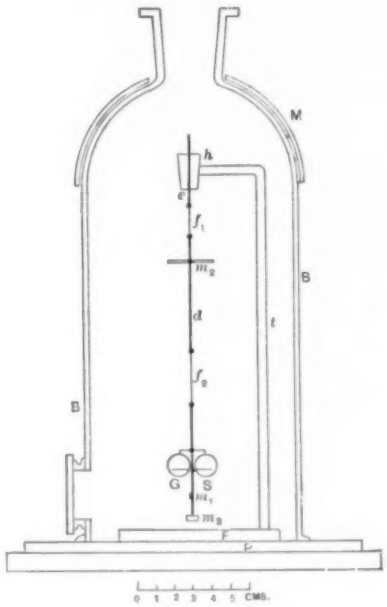


Fig. 2.

tation axis ab was a fine rod of drawn glass. At r, a drawn glass cross-arm c, bent down at either end into the form of a small hook,

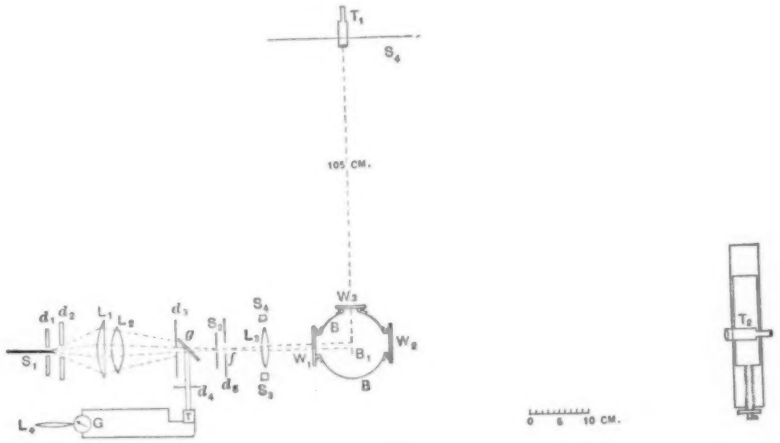


Fig. 3.

was attached. The surfaces G and S, which received the light beam, were circular microscope cover-glasses, 12.8 mm. in diameter and 0.17 mm. thick, weighing approximately 51 mgs. each. Through each glass a hole 0.5 mm. or less in diameter was drilled near the edge, by means of which the glasses could be hung on the hooks on the cross-arm c. Two other drawn-glass cross-arms were attached to the rotation axis at d, one on each side. The cover-glasses slipped easily between these, and were thus held securely in one plane. Further down on ab, a small silvered plane mirror m_1 was made fast at right angles to the plane of G and S. This mirror was polished bright on the silver side so that the scale at S_4 (Fig. 3), could be read in either face. A small brass weight m_3 (Fig. 1), of 452 mgs. mass and of known dimensions, was attached at the lower end of ab. The cover glasses which served as vanes were silvered and brilliantly polished on the silvered sides, and so hung on the small hooks on c that the glass face of one, and the silver face of the other, were presented to the light. A quartz fiber f_2 (Fig. 2), 3 cms. long, was made fast to the upper end of ab, and to the lower end of a fine glass rod d which carried a horizontal magnet m_2. The rod d was in turn suspended by a short fiber to a steel pin e which could be raised or lowered in the bearing h. The whole was carried by a bent glass tube t, firmly fastened to a solid brass foot F, resting on a plane, ground-glass plate P, cemented to a brass platform mounted on three levelling screws not shown in Fig. 2. A bell-jar B, 25 cms. high and 11 cms. in diameter covered the balance. The flange of the bell-jar was ground to fit the plate P. A ground-in hollow glass stopper fitted the neck of the bell-jar, which could thus be put in connection with a system of glass tubes leading to a Geissler mercury pump, a MacLeod pressure gauge, and a vertical glass tube dipping into a mercury cup and serving as a rough manometer for measuring the larger gas pressures employed during the observations. The low pressures were measured on the MacLeod gauge in the usual way. A semicircular magnet M, fitted to the vertical curvature of the bell-jar, was used to direct the suspended magnet m_2, and thus control the zero position of the torsion balance. By turning M through 180°, the opposite faces of the vanes G and S could be presented to the light.

The Arrangement of Apparatus.

A horizontal section of the apparatus through the axis of the light beam, is shown in Fig. 3, which like the other figures is, in its essential features, drawn to scale. The white-hot end of the horizontal carbon S, of a 90° arc lamp, fed by alternating current, served as a source. The arc played against the end of the horizontal carbon from the vertical carbon which was screened from the lenses L_1 and L_2 by an asbestos diaphragm d_2. The lens L_4 projected an enlarged image of the arc and carbons on a neighboring wall, so that the position of the carbons and the condition of the arc could be seen at all times by both observers. The cone of rays passing through the small diaphragm d_2 fell upon the glass condensing lenses L_1, L_2 which formed an image of the carbon at f. At d_3 a diaphragm, 11.25 mm. in diameter, was interposed, which permitted only the central portion of the cone of rays to pass. Just beyond d_3, a plane plate of glass g was placed in the path of the beam and reflected part of the beam through the diaphragm d_4, to a thermopile T, connected with a galvanometer G. The beam which traversed the plate g passed on to a shutter at S_2. The shutter was worked by a magnetic escapement, operated by the seconds contact of a standard clock. The observer at T_1 might choose the second for opening or closing the shutter, but the shutter's motion always took place at the time of the seconds contact in the clock. Any exposure was thus of some whole number of seconds duration. The opening in the shutter was such as to let through, at the time of exposure, all of the direct beam which passed through d_3, but shut out the stray light. It was made to correspond in every way to the diaphragm d_4, so that for all of the reflected beam which passed d_4, the corresponding transmitted portion passed S_2 and no more. The glass lens L_3 focused a sharp image of the aperture d_3 in the plane of the vanes of the torsion balance B_1 under the bell-jar B. The bell-jar was provided with three plate glass windows W_1, W_2, W_3. The first two gave a circular opening 42 mm. in diameter, and the third was used in connection with the telescope T_1, by which an image of the scale S_4 was seen in the small mirror m_1 (Figs. 1, 2). The lens L_3 was arranged to move horizontally between the stops

S_3 and S_4. The stops were so adjusted that when the lens was against S_3 the sharp image of the aperture d_3 fell centrally upon one vane; and when against S_4 the image fell centrally upon the other. This adjustment, which was a very important one, was made by the aid of a telescope T_2, mounted on the carriage of a dividing engine. This was used to observe and measure the positions of the vanes and the rotation axis, as well as the positions of the images of d_3, when the lens L_3 was against the stops S_3 and S_4. For the latter measurements, the vanes could be moved out of the way, by turning the suspension through 90° by the control magnet M (Fig. 2).

METHODS OF OBSERVATION.

The observations leading to the results given later were of three different kinds: (1) The calibration of the torsion balance; (2) the measurement of the pressure of radiation in terms of the constant of the balance, and (3) the measurement of the energy of the same beam in electrical units by the aid of a bolometer described later.

1. The determination of the constant of the torsion balance was made by removing the vanes G and S and accurately measuring the period of vibration. Its moment of inertia was easily computed from the masses and distribution of the separate parts about the axis of rotation. From the moment of inertia, period, the lever arms of G and S, and the distance of the scale S_4, the constant of the balance for a centimeter deflection was found to be 4.65×10^{-5} dynes.

2. In the measurements of radiation pressure, it was easier to refer the intensity of the beam at each exposure to some arbitrary standard which could be kept constant than to try to hold the lamp as steady as would otherwise have been necessary. For this purpose, the thermopile T (Fig. 3) was introduced, and simultaneous observations were made of the relative intensity of the reflected beam by the deflection of the galvanometer G, and the pressure due to the transmitted beam by the deflection of the torsion balance. The actual deflection of the balance was then reduced to a deflection corresponding to a galvanometer deflection of 100 scale divisions. The galvanometer sensitiveness was carefully tested at

intervals during the work, and was found as nearly constant as the character of the observations required. All observations of pressure were thus reduced to the pressure due to a beam of fixed intensity.

At each gas pressure in the bell-jar, at which radiation pressure measurements were taken, two sets of observations were made. In one of these sets, static conditions were observed, and in the other, the deflections of the balance due to short exposures were measured. In the static observations, each vane of the balance was exposed in turn to the beam from the arc lamp, the exposures lasting in each case until the turning points of the swings showed that static conditions had been reached. The combined pressure, due to radiation and gas action would thus be equal to the product of the angle of deflection and the constant of the balance. The torsion system was then turned through 180° by rotating the outside magnet, and similar observations made on the reverse side of the vanes, after which the system was turned back to its first position, and the earlier set of observations repeated, and so on.

The considerations underlying the above method of procedure, are as follows: The beam from the lamp, before reaching the balance, passed through three thick glass lenses and two glass plates. All wave-lengths destructively absorbed by the glass, were thus sifted out of the beam by the time it reached the glass balance vanes. The silver coatings on the vanes absorbed therefore more than the glass. The radiation pressure was always away from the source irrespective of the way the vanes were turned, while the gas action would be exerted mainly on the silvered side of the vanes. As the face of the vane on one side of the balance was silver, and on the other side glass backed by silver, the two forces should act in the same direction on one vane, and oppositely on the other. If each silver coating reflected equally on its two faces, the average of the deflections on the two arms of the balance, should be free in part, from gas action.

This partial elimination of gas action would be more complete but for two reasons: (1) The reflection at the exposed glass face of one vane diminishes the energy incident upon the silver coating behind it and the resultant absorption in the same propor-

tion. (2) The glass faces of the two vanes, when exposed, will not, in all probability, be equally heated. In the case of the vane which receives the light on its silvered face, the glass face can be warmed only by the conduction of heat from the silver coating through the glass, while in the vane receiving light on its glass face, some heat from absorption of the beam in passing through the glass will doubtless be added to this heat due to conduction. Although the vanes, when freshly silvered and polished, were so brilliant on the silvered sides that it was often difficult to tell which face was silver and which glass, the coatings were found in use to deteriorate rapidly, and the silver faces whitened earlier than the glass. After several hours of observing, vanes freshly silvered at the beginning had to be removed and resilvered. A higher rate of deterioration was noticeable when working in low gas pressures than in high.

By the reversal of suspension and averaging the results gained with the suspension direct and reversed, nearly all errors due to lack of symmetry in the balance, or in the position of the light images with reference to the rotation axis; or errors due to lack of uniformity in the distribution of radiant intensity in different parts of the image, as well as errors due to certain differences between the mirrors themselves, could be eliminated.

Static observations were made at eight different gas pressures between 0.06 mm. of mercury and 96 mm. Within this range, as was afterwards shown by the series of semiballistic in connection with the static observations, the gas action varied in magnitude between one-tenth, and 6 or 7 times, the radiation pressure. The gas action was, however, at certain pressures so complicated that no rational way of treating the static measurements at the different gas pressures succeeded in establishing the existence of a constant force in the direction of propagation of the light beam. It was plain, therefore, that further elimination of the gas action must be sought in exposures so short that the gas action would not have time to reach more than a small fraction of its stationary value. This led to the method of semiballistic observations.

If the vibrations of any suspension be undamped, a constant deflecting force, acting for one-fourth of the period of oscillation, will

cause a throw equal to $\sqrt{2}$ times the permanent deflection for the same force. A correction for damping when considerable may also be introduced. The period of the balance as described was 23.1 secs. This was increased to 24 secs. by adding masses to the system. Deflections due to six seconds' exposure were then observed in the same manner, with reversals and all, as has been already described under the static observations. Because of the shorter time involved in making individual observations, a considerably greater number of ballistic measurements were made at each gas pressure. In all the observations yet made, not a single ballistic deflection contrary to the direction of radiation pressure was obtained, and in the static observations, the first throw on exposing was invariably in the radiation pressure direction, irrespective of the direction of the final deflection.

The average ballistic deflection obtained, reduced to the equivalent permanent deflection for each of eight different gas pressures, is given in the accompanying table. The column p gives the gas pressure in the bell-jar in millimeters of mercury, and column d the reduced permanent deflection in millimeters for the radiation pressure.

p	d	p	d
96.3	19.7	33.4	21.1
67.7	21.0	1.2	20.9
37.9	21.6	0.13	26.8
36.5	22.1	0.06	23.2
Ave.			22.5

For gas pressures between 45 and 30 mm. the gas action is small and increases toward both higher and lower pressures in the range studied. Taking the product of the average deflection in cms. by the constant of the torsion balance, the radiation pressure was $2.25 \times 4.65 \times 10^{-5} = 1.05 \times 10^{-4}$ dynes.

The Bolometer.

To test the above value of radiation pressure with the theory, it was necessary to measure the energy of the radiation causing the

pressure. This was attempted with the aid of a bolometer of special construction.

On a sheet of platinum 0.001 mm. thick, rolled in silver (by the firm Sy & Wagner, Berlin), a circle P (Fig. 4), 11.3 mm. in diameter, was drawn. The sheet was cut from the edges inward to the circumference of the circle, in such a way as to leave five principal strips A, B, C, D, E, connected to the circle in the manner shown. Other narrower strips, as c, m, n, o, etc., were left to give the disk additional support. The disk, by means of the connecting arms, was mounted with asphalt varnish centrally over a hole 14 mm. in diameter, bored through a slab S cut from a child's school slate. Portions of the silver not to be removed by the acid were carefully covered by the asphalt varnish. Thus on the strips A and B, the silver was protected to the very edge of the circle, while on all the other arms, the silver was left exposed back to the edge of the boring in the slate. The whole system was then plunged into warm nitric acid, and the silver eaten away from all unprotected surfaces, leaving only the thin platinum sheet, which was blackened by elec tric deposition of platinum, by the method used in the manufacture of the Reichsanstalt bolometers. At A, B, C, D, E, holes were bored extending through the slate, and copper washers were soldered to the silver strips, and binding posts were attached.

The torsion balance was removed from under the bell-jar, the bolometer put in the place of one of the vanes, and the bell-jar replaced. Connections to the bolometer were made as schematically shown in Fig. 4. The disk P was the exact size of the light image thrown on the vanes in the pressure measurements, and the intention was to heat the disk by allowing the image to fall on it, and then with the light turned off, to heat it to the *same temperature* by sending a current through it from A to B. If r be the resistance from A to B in ohms, when exposed to the lamp, and i be the current in ampères which gives the same temperature in P as that given by the absorbed radiation, then $i^2r \times 10^7$ will be the activity of the beam in erg-seconds. The temperature of the disk, whether exposed to the radiation or heated by the current, was shown by the resistance of the disk in the direction C to D and E which was

made one arm of a Wheatstone Bridge. The relation of the heating current to the bridge was adjusted as follows: With the key K open, so that no current flowed through the bridge, the heating current from six storage cells B_2 was turned on, and the sliding contact at F so set that the bridge galvanometer zero was not changed by reversing the heating current. The equipotential point to c was found very near the middle of the wire ab, which showed the current distribution of P to be symmetrical with respect to a diameter at right angles to AB. The key K was then closed making the bridge current, and the bridge was balanced. The bolometer was next exposed to the radiation, and simultaneous observations were made on the two galvanometers G (Fig. 3) and G_1 (Fig. 4) and the deflection of the latter, was reduced to that corresponding to a deflection of 100 divisions of galvanometer G, as was done in the radiation pressure observations. During the pressure, as well as the bolometer measurements, the electric lamp was regulated by the observer at the galvanometer G, and the lamp held reasonably close to this standard value. The reductions were, therefore, of the simplest kind. After shutting off the light, the heating current was turned on and regulated by means of the variable resistance R_1 (Fig. 4), so that nearly the same throw was obtained from the galvanometer G, as when the bolometer was exposed to the lamp. All deflections of the galvanometer G_1 were taken with the bridge current both direct and reversed, to eliminate any local disturbances in the bridge. With the heating current on, galvanometer deflections were read with the heating current both direct and reversed. The heating current was read in ampères from a Siemens & Halske direct-reading precision milliampèremeter. From repeated observations the current which gave the same heating effect as the light beam, was $i = 0.865$ amp. The resistance between the binding posts A and B, was measured with the lamp on, and gave $r = 0.278$ ohm. The intensity of the beam in erg-seconds was thus $= 0.278 \times 0.75 \times 10^7$.

Considering the beam as a cylinder containing energy which is transmitted at the velocity v of radiation, the energy contained in a length of 3×10^{10} cms. would, according to the bolometer results be $i^2 r \times 10^7$, and the consequent pressure in dynes, against the totally

absorbing end of the cylinder must, according to Maxwell, equal the energy per unit length, or

$$p = \frac{i^2 r \times 10^7}{v}.$$

If the incident beam falls upon a totally reflecting surface the energy per unit volume is doubled and the deduction from Maxwell is that the pressure is equal to $\frac{2i^2 r \times 10^7}{v}$.

According to Bartoli and Boltzmann, the pressure due to a beam totally reflected must on thermodynamic grounds also be $\frac{2i^2 r \times 10^7}{v}$. If the beam is but partially reflected, however, the pressure would be

$$p = \frac{(1 + r_1) i^2 r \times 10^7}{v},$$

where r_1 equals the percentage of the incident energy reflected Considering the character of the light from the arc lamp, and the heavy infra-red absorption of the glass masses traversed, the reflecting power of the bright silver coatings was estimated to be nearly that for the wave-lengths of the D lines, or about 92 per cent.[1] Putting $1 + r = 1.92$ we have from the bolometer results

$$\frac{1.92 \times 0.278 \times 0.75 \times 10^7}{3 \times 10^{10}} = 1.34 \times 10^{-4} \text{ dynes}$$

as the pressure which the torsion balance should have shown, instead of the observed value 1.05×10^{-4}. Some of the mirrors used in the pressure observations were already well below this maximum reflecting power, so that the value 1.34×10^{-4} should doubtless be still further reduced, but no quantitative va ue can be assigned to such a correction.

Taking the results as they stand, the measured radiation pressure is to the radiation pressure which the theory applied to the bolometer measurements would require as 1.05 : 1.34 or as 78 : 100.

[1] E. F. Nichols, PHYS. REV., 4, p. 303 also F. Paschen, Ann. Phys., 4, p. 304, 1901.

Some sources of uncertainty in the pressure measurements have already been mentioned, but certain sources of error in the bolometer measurements in which the nature of the effect upon the result is known, should be more clearly indicated.

1. Errors in the bolometer which would tend to produce a greater divergence between the two results obtained are:

(*a*) The reflection of radiation by the platinum-black coating (this error is small) and (*b*) the heat conductivity of the black coating. In the case of the lamp, the transformation of radiant energy into heat takes place near the outer surface of the platinum-black covering, and the electrical resistance of P is affected only after the heat has passed by conduction through this coating to the sheet of platinum underneath. In the case of heating by the current, on the other hand, the heat is generated in the conducting sheet directly, and is dissipated at the outer surface after conduction through the black layer. This error is probably small also.[1]

2. Errors which would tend to bring the two results into closer agreement are two in number. (*a*) The measured resistance between the binding posts A and B must be greater than that of the disk P by the resistance of the silver strips leading from the binding posts on both sides to P, and by any contact resistances involved. The magnitude of this error is unknown, but it may be large. (*b*) The distribution of current lines of flow for both heating current and bridge current would be such as to cause an error in the result of the same sign as the resistance error. The maximum heating would occur where the silver strips A and B join the disk, for here the stream lines will be most congested; on the other hand, the stream lines of the bridge current in these regions will be most sparse because nearly all the lines traversing the disk on the two sides will be drawn off into the edges of these same silver strips by the higher conductivity of the latter. This error may also be considerable. In a new bolometer now under construction the errors due to false resistance and unfavorable distribution of flow lines will be greatly reduced. Another series of radiation pressure measure-

[1] See Kurlbaum: Temperaturdifferenzen zwischen der Oberfläche und dem Innern eines strahlendes Korpers. Ann. Phys., 2, p. 554.

ments, made under more favorable conditions than those here reported, is also in progress.

The writers believe that the observations already in hand are sufficient to prove experimentally the existence of a pressure, not due to gas molecules, of the nature and order of magnitude of radiation pressure, but toward a close quantitative measurement of this pressure much remains still to be done.

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